

U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-251 664

FLARE SYSTEMS STUDY

LOCKHEED MISSILES AND SPACE COMPANY,
INCORPORATED

PREPARED FOR
INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY

MARCH 1976

TECHNICAL REPORT DATA (Please read instructions on the reverse before completing)			
1. REPORT NO. EPA-600/2-76-079		3. RECIPIENT'S ACCESSION NO. PB-251-664	
4. TITLE AND SUBTITLE Flare Systems Study		5. REPORT DATE March 1976	
		6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S) M. G. Klett and J. B. Galeski		8. PERFORMING ORGANIZATION REPORT ID LMSC-HREC TR D390190	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Lockheed Missiles and Space Co., Inc. Huntsville Research and Engineering Center 4800 Bradford Drive Huntsville, Alabama 35807		10. PROGRAM ELEMENT NO. 1AB015; ROAP 21AXM-030	
		11. CONTRACT/GRANT NO. 68-02-1331, Task 3	
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; 8/74-5/75	
		14. SPONSORING AGENCY CODE EPA-ORD	
15. SUPPLEMENTARY NOTES Project officer for this report is Max Samfield, Mail Drop 62, Ext 2547.			
16. ABSTRACT The report gives results of a study of industrial flare technology for control of gaseous combustible emissions from stationary sources. The study included evaluation of present engineering technology, evaluation of existing flare systems, assessment of present practices and problems, determination of major sources, and development of research recommendations including potential applications. The report summarizes emissions data, and gives emission factors for hydrocarbon waste streams, based on limited available data. It recommends the selection of applicable flare systems and components for flaring given waste streams. It discusses potential problems which may affect design and component selection. It gives cost guidelines based on discussions with flare vendors and users.			
17. KEY WORDS AND DOCUMENT ANALYSIS			
a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	
Air Pollution Iron and Steel Industry		Air Pollution Control	
Flammable Gases Chemical Engineering		Stationary Sources	
Exhaust Gases Cost Effectiveness		Industrial Flares	
Hydrocarbons			
Industrial Processes			
Refineries			
		13B 11F	
		11G 07A	
		21B 14A	
		07C	
		13H	
		PRICES SUBJECT TO CHANGE	
19. DISTRIBUTION STATEMENT Unlimited		19. SECURITY CLASS (This Report) Unclassified	
		20. SECURITY CLASS (This Report) Unclassified	
		131 600-2-25	

110179

EPA-600/2-76-079

March 1976

PB 251 664

Environmental Protection Technology Series



EPA-600/2-76-079
March 1976

FLARE
SYSTEMS STUDY

by

M. G. Klett and J. B. Galeski

Lockheed Missiles and Space Co., Inc.
4800 Bradford Drive
Huntsville, Alabama 35807

Contract No. 68-02-1331, Task 3
ROAP No. 21AXM-030
Program Element No. 1AB015

EPA Task Officer: Max Samfield

Industrial Environmental Research Laboratory
Office of Energy, Minerals, and Industry
Research Triangle Park, NC 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

FOREWORD

This study of industrial flare technology was conducted under Task 3 of Contract EPA-68-02-1331 by personnel of Lockheed Missiles & Space Company, Inc., Huntsville Research & Engineering Center, Huntsville, Alabama, for the Controls System Laboratory of the Environmental Protection Agency, Research Park Triangle, North Carolina. Dr. Max M. Samfield was the EPA Task Officer. In addition to the authors, Dr. S. V. Bourgeois participated in the study as Lockheed Project Manager.

The authors are grateful for the cooperation and time of the staffs of the equipment manufacturers, flare users and the Air Pollution Control Districts, who provided much of the information upon which this study is based.

TABLE OF CONTENTS

Section		Page
	FOREWORD	ii
I	INTRODUCTION AND SUMMARY	1
	1.1 Introduction	1
	1.2 Summary	1
	1.2.1 Elevated Flares	2
	1.2.2 Low-Level Enclosed Flares	2
	1.2.3 Auxiliary Equipment	2
	1.2.4 Costs	3
	1.2.5 Flare Performance and Emissions	3
	1.2.6 Proposed Research and Development Programs	4
II	BACKGROUND	5
	2.1 Applications of Flaring for Waste Gas Disposal	5
	2.2 Flaring Methods	7
III	COMMERCIALY AVAILABLE FLARE SYSTEMS	9
	3.1 Elevated Flares	9
	3.1.1 Flare Tips	9
	3.1.2 Gas Traps	12
	3.1.3 Pilot and Ignition System	18
	3.1.4 The Stack and Its Support	18
	3.1.5 Water Seals, Flame Arrestors and Knockout Drums	18
	3.2 Ground Flares	22
	3.3 Forced Draft Flares	22
	3.4 Comparative Costs of Flare Systems	27
IV	FLARE DESIGN CRITERIA	29
	4.1 Selection of Applicable Flare System	29
	4.2 Flammability Limits and Flame Stability	30
	4.3 Flare Emissions	32

TABLE OF CONTENTS (Continued)

Section		Page
IV	4.3.1 Thermal Emissions and Luminosity	32
	4.3.2 Noise Emission	33
	4.3.3 Smoke and Particulate Emissions	36
	4.3.4 Chemical Emissions	39
	4.3.5 Oxidation Products	40
	4.3.6 Other Gaseous Emission Sources	41
	4.3.7 Dispersion of Chemical Emissions and Flammable Gases	41
	4.3.8 Air Pollution Rules and Regulations Affecting Flares	51
	4.3.9 Flare Emission Factors	53
	4.4 Flare Safety	54
	4.4.1 Explosion Potential	54
	4.4.2 Vapor Purging	55
	4.4.3 Molecular Seals	56
	4.4.4 Fluidic Seal	56
	4.4.5 Explosion Suppression Systems	56
	4.4.6 Water Seals and Flame Arrestors	56
	4.4.7 External Fires and Emissions	58
	4.4.8 Knockout Drum Sizing and Design Criteria	58
	4.4.9 Thermal Radiation Hazards	60
V	RECOMMENDED DESIGN METHOD	71
	5.1 Elevated Flare System	71
	5.1.1 Required Design Information	71
	5.1.2 Flare Burner Diameter	72
	5.1.3 Utility Requirements	75
	5.1.4 Flare Height	77
	5.1.5 Supporting Structures	79
	5.1.6 Auxiliary and Control Components	79
	5.1.7 Endothermic Flaring - Low Btu Gas Streams	80
	5.2 Low-Level Flare	81
VI	SAMPLING AND ANALYSIS TECHNIQUES	82
	6.1 Present Sampling Practices and Problems	82
	6.2 Analytical Techniques	83
	6.2.1 Hydrocarbons	84
	6.2.2 Oxidized Hydrocarbons, Carbon Monoxide, Carbon Dioxide	84

TABLE OF CONTENTS (Continued)

Section		Page
VI	6.2.3 Nitrogen Oxides	84
	6.2.4 Sulfur Dioxide	87
	6.3 Long Path Remote Sensing Techniques	87
VII	FLARE LOADINGS AND EMISSIONS FOR VARIOUS INDUSTRIES	90
	7.1 Questionnaire Format and Circulation	90
	7.2 Refinery Questionnaire Results	90
	7.3 Impact of Flares on Refinery Emissions	97
	7.4 Iron and Steel Mills Questionnaire Results	99
	7.5 Impact of Flares on Iron and Steel Mill Emissions	100
	7.6 Manufacturing Chemists Questionnaire Results	104
	7.7 Summary of Flare Loadings	106
VIII	RECOMMENDED RESEARCH PROGRAM	107
	8.1 Theoretical Analysis of Combustion Modifications Applicable to Flaring	107
	8.1.1 Summary and Objectives	107
	8.1.2 Background	107
	8.1.3 Validation of the Analytical Model	109
	8.1.4 Evaluation of Flare Design Modifications	109
	8.1.5 Priority	109
	8.2 Evaluation of Remote Sampling Methods	109
	8.2.1 Summary and Objectives	109
	8.2.2 Background	109
	8.2.3 Summary of Remote Sampling Technology	109
	8.2.4 Remote Sampling Field Studies	110
	8.2.5 Priority	110
	8.3 Application of Flaring to Control of Gaseous Emissions	110
	8.3.1 Summary and Objectives	110
	8.3.2 Background	110
	8.3.3 Theoretical Analysis	110
	8.3.4 Experimental Analysis	113

TABLE OF CONTENTS (Continued)

Section		Page
VIII	8.3.4 Experimental Analysis	113
	8.3.5 Priority	113
	8.4 Economic Analysis of Waste Stream Recovery and Alternate Disposal Methods	113
	8.4.1 Summary and Objectives	113
	8.4.2 Background	114
	8.4.3 Identify Economic Considerations Now Used to Determine Whether a Given Flared Stream has Sufficient By-Product Value for Recovery	114
	8.4.4 Identify Alternative Uses of Low Pressure Flammable Hydrocarbon Gases	115
	8.4.5 Evaluation of Alternative Disposal Methods	115
	8.4.6 Priority	115
	8.5 Emission Factors for Elevated Flare Systems	115
	8.5.1 Summary and Objectives	115
	8.5.2 Background	115
	8.5.3 Site Selection and Evaluation of Sampling Methods and Hardware	116
	8.5.4 Field Testing of Elevated Flare Systems	116
	8.5.5 Priority	116
IX	REFERENCES	117

SECTION I

INTRODUCTION AND SUMMARY

1.1 Introduction

This report presents the results of a study of emissions from flare systems. Flares are used for the control of gaseous combustible emissions from stationary sources. The scope of the study includes an evaluation of existing flare systems, an examination of flare design and sizing criteria, recommended design methods and features, an assessment of present emission problems and a recommended research program for flare emissions control. Information was obtained from the published literature, equipment manufacturers, equipment users, air pollution control agencies and universities. Visits were made to many of these sources of information in order to hold detailed technical discussions about the design and performance of flare systems.

Flaring is intended primarily as a safety measure for disposing of large quantities of gases during plant emergencies. Flows are typically intermittent with flow rates of several million cubic feet an hour during major upsets. Continuous flaring is generally limited to flows not greater than a few hundred cubic feet an hour. Since flaring is relatively inexpensive, this technique has been suggested for the control of gaseous combustible emissions from stationary sources. However, emissions from flares could also create a potential problem. This study was carried out with two objectives in mind. One was to determine the potential of flares as a control system and the second was to assess the emission hazards of present industrial flares.

Section II of this report explains the different applications of flaring waste gases. Section III describes the commercially available flare systems and gives comparative cost data. Section IV discusses flare design criteria including in some detail the two main problem areas of flare emissions and safety. Section V presents recommended design methods; Section VII discusses present flare loadings for various industries and their impact on emissions; Section VIII contains a recommended flare research program.

1.2 Summary

Commercially available flare systems are of two basic types - elevated and ground flares. Presently, these serve separate functions; elevated flares are used primarily for disposal of gaseous wastes generated during plant emergencies such as during power failure, plant fires, component failure and other overpressure situations in which discharge directly to the atmosphere could result in explosion hazards. Elevated flares are therefore used primarily in conjunction with vapor relief collection systems in large-scale chemical manufacturing or petroleum refining operations. Other limited applications include venting of storage tanks and loading platforms.

Although steam, water and air are frequently injected into the elevated flare burner to reduce smoke and luminosity, expedient vapor disposal rather than pollution control has been the design emphasis. Recently

developed low-level flare systems represent a departure from conventional design. With recent emphasis reducing noise, chemical emissions, heat and luminosity, low-level flares have become increasingly popular for disposing of routine discharges. These include disposal of flammable gases leaking from process and relief valves, process waste streams, and excess or off-specification product.

1.2.1 Elevated Flares

Elevated flare systems provide a means for disposal of gaseous waste streams with an almost unlimited range of flows and a minimal pressure drop of 0 to 60 inches H_2O . As such, elevated flares provide a unique function which cannot be duplicated by other types of combustion equipment.

Design criteria for elevated flare systems are oriented almost exclusively toward safe rather than efficient combustion of gaseous wastes. Accordingly, sizing calculations presently available are based on allowable pressure drop (Section 5.1.2) and dispersion of thermal radiation (Section 5.1.4) or the dispersion of toxic gases when a flare-out occurs (Section 4.1.7). Discharge of liquids into the flare system can cause problems, and "knock-out" or liquid disentrainment drums are required for liquid removal.

1.2.2 Low-Level Enclosed Flares

Low-level flares with enclosed combustion are being used in conjunction with the elevated flare in response to recent emphasis on pollution. These are described in detail in Section III. The study indicates that low-level flares, although relatively expensive to build and maintain, are effective in reducing noise and thermal emissions.

Relatively little information has been found on sizing and design of low-level flares. The normal configuration for construction of a low-level flare involves a steel outer shell, lined with refractory material. The outer shell serves to conceal the flame and prevent thermal and luminous radiation. As in other types of combustion equipment, the refractory also protects the steel shell from direct exposure to the effects of high temperatures and corrosive materials, and to improve combustion efficiency by minimizing heat losses. Refractory thicknesses typically varies from about 4 to 8 inches. The refractory used results in a sluggish response to abrupt changes in gas flow and adds considerably to the construction and maintenance costs of a low-level flare. Because of the slow heatup associated with refractory construction, the low-level flare is normally used only for low or continuous flow rates, with an elevated flare of conventional design used to accommodate sudden upsets. An elevated flare must be associated with low-level flare applications in most conventional designs.

1.2.3 Auxiliary Equipment

Auxiliary equipment for the flare system includes igniters, pilots and safety-oriented equipment described in Sections 3.1, 4.4 and 5.1.6.

Knockout drums are normally provided for removal of liquids from the flared stream. Water seals and, less frequently, flame arrestors are used to isolate the flare stack from the vent collection system. Purge gas generators and vapor traps serve to prevent the formation of explosive mixtures within the flare stack. Maintenance of the liquid level in water seals and disentrainment drums is critical; liquid level control and alarm systems are available for these systems. Pilot burners are also frequently equipped with flame detection and alarm systems.

1.2.4 Costs

Capital costs for low-level flares and various types of elevated flares are given in Section 3.4. This information is based on discussions with flare vendors and users.

Elevated flare equipment costs vary considerably because of the disproportionate costs for auxiliary and control equipment and the relatively low cost of the flare stack and burner. As a result, equipment costs are rarely diameter-dependent. Typical installed costs range from \$30,000 to about \$100,000. Low-level flares are approximately ten times more expensive for similar capacity ranges.

Operating costs are determined chiefly by fuel costs for purge gas and pilot burners, and by steam required for smokeless flaring. Steam and other requirements are discussed in Sections 5.1.3 and 5.1.7. On the basis of 30 cents per million Btu's fuel requirements, typical elevated flare stack operating costs (2-foot-diameter stack) are about \$1,500 per year.

1.2.5 Flare Performance and Emissions

Since flaring has traditionally been used for the safe disposal of gases discharged under emergency conditions, performance standards relating to combustion efficiency and gaseous emissions are limited. Probable air pollutants from elevated flares include CO, unburned hydrocarbons, aldehydes, and particulates as expected from any combustion process involving large, turbulent diffusion flames. These emissions result from flame quenching. Relatively low flame temperatures are typically observed for both elevated and low-level flares, probably resulting in low NO_x emission factors compared to other types of industrial combustion equipment.

Results of a survey to determine flare loadings and estimated flare emissions are discussed in Section VII. It was found that the average yearly emissions from flares constitute just a small fraction, less than 1%, of the average yearly plant* emissions. Total flare emissions over a year's time therefore probably only have a small impact on total plant

* Representative plants include U.S. petroleum refineries, iron and steel mills and chemical manufacturing facilities.

emissions. However, because of the intermittent nature of flaring, the majority of flare emissions are concentrated into just a few minutes of actual flaring. During this time five or more times the normal plant emissions are released into the atmosphere.

1.2.6 Proposed Research and Development Programs

Programs have been developed to provide technology where deficiencies exist, to generate the data required to evaluate combustion modifications and extend the application of flaring to air pollution control.

Since little quantitative performance data were found in this study, field testing of elevated and enclosed ground level flare systems is recommended. Testing should be done to determine the concentration and characteristics of flare combustion products as well as the mass rate of emissions in order to evaluate the efficiency of flare systems as a control device.

A combustion research program is recommended to fill the gaps existing in the technology of large diffusion flames. For this study, construction of a large scale flare burner and combustion chamber is recommended. Part of the rationale and incentive for this program is that many industrial flames are of the turbulent-diffusion-flame type.

SECTION II

BACKGROUND

In many industrial operations, and particularly in chemical plants and petroleum refineries, large volumes of combustible waste gases are produced. These gases result from undetected leaks in the operating equipment, from upset conditions in the normal operation of a plant where gases must be vented to avoid dangerously high pressures in operating equipment, from plant start ups and from emergency shut downs. Large quantities of gases may also result from "off-spec" product or excess product which cannot be sold. Flows are typically intermittent with flow rates during major upsets of several million cubic feet per hour.

The preferred control method for excess gases and vapors is to recover them in a blowdown recovery system. However, large quantities of gas, especially those produced during upset and emergency conditions, are difficult to contain and reprocess. In the past all waste gases were vented directly into the atmosphere. However, widespread venting caused safety and environmental problems. In practice, therefore, it is now customary to collect such gases in a closed flare system and to burn these gases as they are discharged from an elevated flare stack or alternately the gases may be discharged and burned at ground level usually with shielding for the flame.

The flare system is used primarily as a safe method for disposing of excess waste gases. However, the flare system itself can present additional safety problems. These include the explosion potential of a flare, thermal radiation hazards from the flame, and the problem of toxic asphyxiation during flame-out. Aside from safety there are several other problems associated with flaring which must be dealt with during the design and operation of a flare system. These problems fall into the general area of emissions from flares and include the formation of smoke, the luminosity of the flame, noise during flaring and the possible emission of air pollutants during flaring.

2.1 Applications of Flaring for Waste Gas Disposal

There are three main considerations in deciding whether to flare a waste gas. These are: (1) the variability of the flow of the waste stream, (2) the expected maximum volume of the stream to be flared, and (3) the heat content of the waste stream.

A high variability of flow of the waste stream is probably the most important factor. A flare is designed to operate for practically an infinite "turndown" range of flows. Alternate waste gas disposal systems such as incinerators or afterburners need an adequate control on the flow of waste gases and can only be used for continuous or at least fairly continuous gas flows.

The volume of the waste stream to be disposed is also an important factor. With very large volumes of gas, direct flame combustion by incineration or a flame afterburner device becomes impractical due to the size of equipment needed. However, capacity for an elevated flare can be increased easily by increasing the diameter of the stack. A typical small flare with a four-inch diameter stack has a capacity of 30,000 scfh. A normal refinery flare with a capacity of 5,000,000 scfh would need only a 36-inch diameter flare stack.

The heat content of a waste gas falls into two classes. The gases can either maintain their own combustion or they cannot maintain their own combustion. In general, a waste gas with a heating value greater than 200 Btu/ft³ can be flared successfully. The heating value is based on the lower heating value of the waste gas at the flare. Below 200 Btu/ft³ enriching the waste gas by injecting a gas with a high heating value may be necessary. The addition of such a rich gas is called endothermic flaring. Gases with a heating value as low as 60 Btu/ft³ have been flared but at a significant fuel demand (Ref. 1). It is usually not feasible to flare a gas with a heating value below 100 Btu/ft³ (Ref. 2). If the flow of low BTU gas is continuous, incineration can be used to dispose of the gas. For intermittent flows, endothermic flaring is the only possibility.

Flares are well suited for disposing of intermittent flows of large and small volumes of waste gases that have an adequate heat value to sustain combustion. For intermittent flows of low heating value waste gases, additional fuel must be added to the waste stream in order to flare. Since the value of the additional fuel can become considerable and is completely lost during flaring, endothermic flaring can become expensive. However, if intermittent flows of low heat waste gases are in large volumes, the only practical alternative to flaring is to vent the gases directly to the atmosphere. This is usually unacceptable for environmental reasons.

Most flares are used to dispose of the intermittent flow of waste gases. There are some continuous flares but they are used generally for small volumes of gases on the order of 500 cfm or less. The heating value of larger continuous flows of a high heat waste stream is usually too valuable to waste in a flare. Vapor recovery or the use of the vapor as fuel in a process heater is preferred over flaring. For large continuous flows of a low heating value gas, auxiliary fuel must be added to the gas in order to flare. It is much more efficient to burn the gas in an enclosed incinerator rather than in the flame of a flare. For small continuous flow of gases, flares are sometimes used even though fuel or heat is either lost or wasted. In these cases the equipment costs are sometimes more important than fuel savings and a flare is more economical to use.

Flares are mostly used for the disposal of hydrocarbons. Waste gases composed of natural gas, propane, ethylene, propylene, butadiene and butane probably constitute over 95% of the material flared. Flares have been used successfully to control malodorous gases such as mercaptans and amines (Ref. 3). However, care must be taken when flaring these gases. Unless the flare is very efficient and gives good combustion, obnoxious fumes can escape unburned and cause a nuisance (Ref. 4).

Flaring of hydrogen sulfide should be avoided because of its toxicity and low odor threshold. In addition, burning relatively small amounts of hydrogen sulfide can create enough sulfur dioxide to cause crop damage or local nuisance (Ref. 5). In recent years gases whose combustion products may cause problems, such as those containing hydrogen sulfide or chlorinated hydrocarbons, have not been recommended for flaring.

2.2 Flaring Methods

The elevated flare is the most common type of flare system in use today. In this flare, gas is discharged without substantial premixing, and ignited and burned at the point of discharge. Combustion of the discharged gases takes place in the ambient atmospheric air by means of a diffusion flame. This type of combustion often results in an insufficient supply of air and thus a smoky flame. A smokeless flame can be obtained when an adequate amount of combustion air is mixed sufficiently with the gas so that it burns completely. Smokeless burning is usually accomplished by injecting steam into the flame. The modern elevated flare allows large volumes of waste gases to be burned safely and inexpensively. However, the elevated flare can also present other emission problems including the emission of noise, light and chemical air pollutants into the atmosphere.

A second type of flare often found is the ground flare. A ground flare consists of a burner and auxiliaries located at or near ground level. The burner may be with or without shielding but it must allow for the free escape of the flame and combustion products. Ground flares have the advantage of being able to have the flame shielded. Compared to elevated flares they either require more land if unshielded or the burners, controls and shielding may be more expensive than a stack. Also if the ignition or pilot system fails, the ground flare cannot disperse the gases as well as an elevated flare.

A third system which has been recently developed and is being employed more frequently, particularly where noise luminosity and smoke formation are severely criticized by local residents, is an enclosed "low-level" ground flare used in conjunction with an elevated flare. In more than 90% of the flare occurrences the load to the flare is less than 10% of design capacity of a flare stack (Ref. 2). The "low-level" ground flare is designed to handle most of the flare occurrences, and the remaining large releases use both systems. This system, called an integrated flare, although expensive can greatly reduce smoke, noise and light emissions that cause complaints from local residents.

Forced draft flaring, where combustion air is mechanically blown to pre-mix with the gas before igniting, is ideal as far as combustion is concerned. This type of flare achieves smokeless burning without the use of steam injection. However, this method has a limited turndown ratio and requires a much larger flare stack for the added combustion air. While this approach has been utilized for some special applications, mostly in places where smokeless burning is required but steam is not available, it has generally been found uneconomical for most uses.

The use of air-inspiring burners for premixed air has also been attempted with flares. This type of operation requires the gas to be supplied at substantially constant rate and pressure of the order of 1 to 4 psig. In many cases such pressure cannot be made available because of limitations of the vent gas collecting system. For air-inspiring installations it is also generally necessary to provide a number of burners of different capacities to handle the wide range of venting rates normally encountered. Flare systems based on this principle have been largely unsuccessful.

Usually, if there is a continuous flow of gas, a vapor recovery system is considered. While the collection, storage, and return of gas is expensive, the continuous wasting of gas may be much more expensive. The capital expenditures to store and recompress immense volumes released intermittently and irregularly usually exceeds the operating expense of flaring the gas. Many plants are now using their flare system in conjunction with a vapor recovery system. They have a triad system for control of waste gases which consists of a vapor recovery system, a low-level flare for most of the flare occurrences which overload the vapor recovery system and an elevated flare for large releases which overload the low-level flare.

Horton et al., (Ref. 6) have discussed what they feel is the future answer to reducing the possible load to a flare. The nuclear power industry has installed highly reliable instrumented systems to eliminate the need for relief valves and still protect a system from overpressure (Ref. 7). However, these systems have not achieved wide use in the chemical or petroleum industry.

The real source of most pressure in gas-liquid systems is heat. Fired heaters and heat exchangers create large volumes of gas which must be relieved. A highly reliable means for automatically cutting off heat, when the pressure reaches a specified value, would decrease or eliminate the need for a safety relief valve. It would therefore decrease the quantity of gas sent to the flare. Reliability is usually assured by independent and redundant instrumentation (Ref. 7).

The high integrity protection system can never totally eliminate all safety relief valves in a plant and thus the need for a flare. However, the load to the flare would be greatly reduced with the flare being used only in major emergency situations.

SECTION III

COMMERCIALLY AVAILABLE FLARE SYSTEMS

In general there are three types of flare systems in use today, the elevated, ground and forced draft flare. This section will describe the equipment available for flaring waste gases by these systems and will also present relative cost data for the different systems.

3.1 Elevated Flares

The modern elevated flare system is made up of several components including the flare tip, some type of gas trap directly below the tip, a pilot and ignition system at the top of the flare tip, and the stack and its support. When smokeless burning is required, a steam injection system must also be provided at the top of the flare. Water seals and knockout drums are also usually required for safety reasons. Figure 3-1 shows a schematic of a typical elevated flare system.

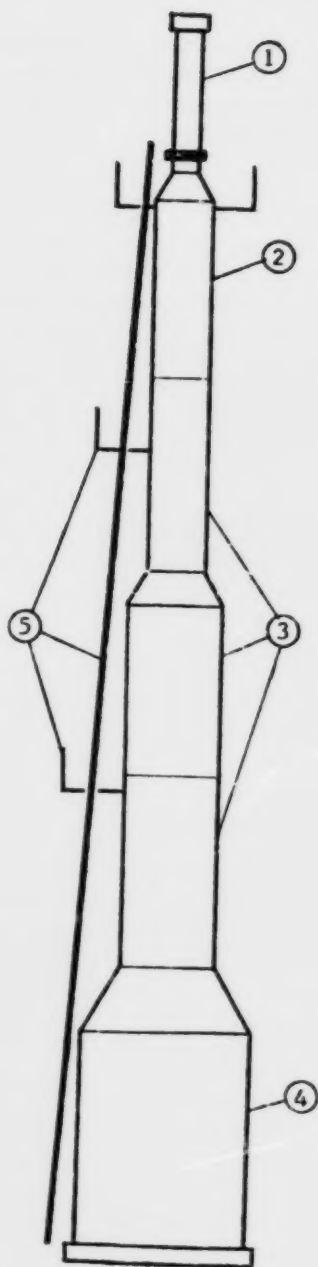
3.1.1 Flare Tips

A flare tip must be capable of operating over a wide range of turndown ratios. To achieve this, the flare must have excellent flame holding ability and mixing characteristics. Flameholding is ensured by providing multiple continuous pilots around the combustion tip and by providing a flame stabilization ring on the combustion tip. Figure 3-2 shows the standard flare tips available from John Zink Company. The flare tip is usually made of stainless steel or some other high temperature and corrosion-resistant alloy.

Smokeless burning can be achieved with special flare tips which inject water, natural gas or steam into the flame thereby increasing air-gas mixing to ensure complete combustion. Water injection has many disadvantages including ice formation in the winter, a mist in the summer, the tremendous pressure head needed for an elevated flare and a turndown ratio much less than steam, making control very difficult with the possibility of quenching the flame. Natural gas has also been used to inject into the flame for smokeless burning but only in the case where the gas itself has no value since it is also burned during flaring. For these reasons steam is the most common utility used for smokeless burning.

There are two basic steam injection techniques used in elevated flares. In one method steam is injected from nozzles on an external ring around the top of the tip. In the second method the steam is injected by a single nozzle located concentrically within the burner tip. Vendors use various types of nozzles to create a circular, swirl, fan, jet or Coanda effect.

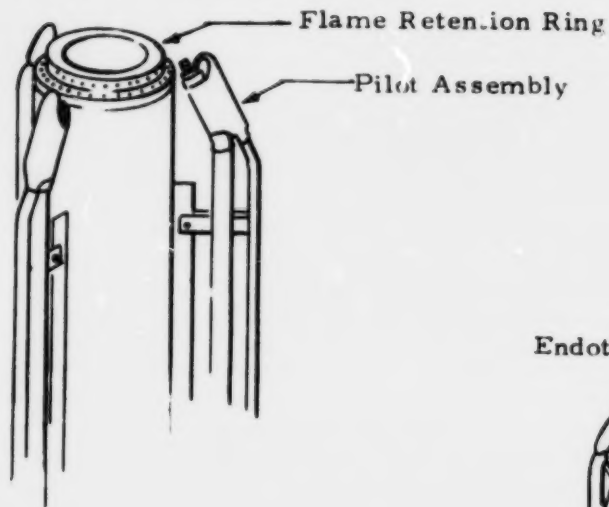
In recent years environmental regulations have required flares to be smokeless for large turndown ratios. To ensure satisfactory operation under varied flow conditions, the two types of steam injection have been combined into one tip. The internal nozzle provides steam at low flow



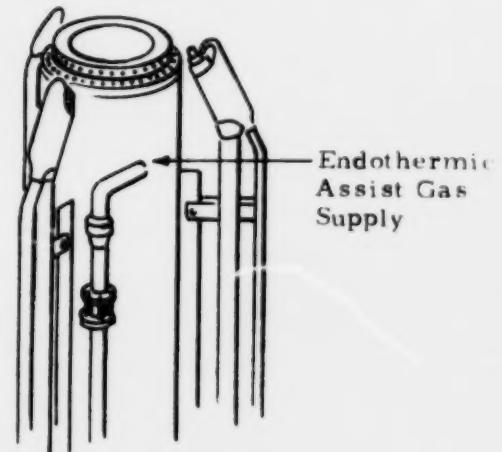
- ① Flare Burner and Location of Fluidic Seal
- ② Gas Trap
- ③ Riser Sections
- ④ Entry, Disentrainment or Water Seal
- ⑤ Ladders and Platforms

Fig. 3-1 - Integrated Flare Stack Components

Utility Field Flare Tip



Endothermic Field Flare Tip



Smokeless Field Flare Tip

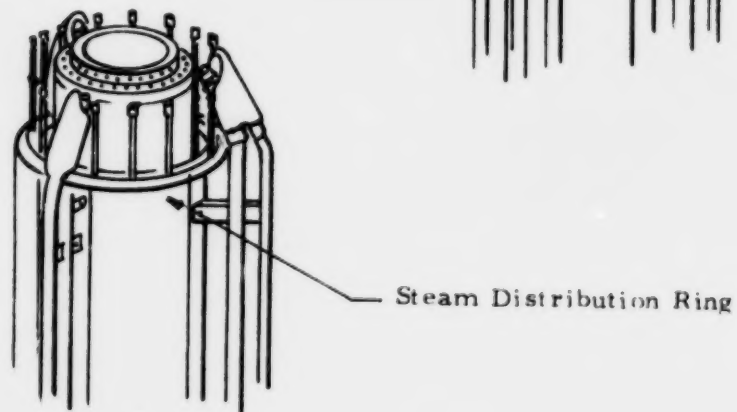


Fig. 3-2 - Flare Tips from John Zink Company

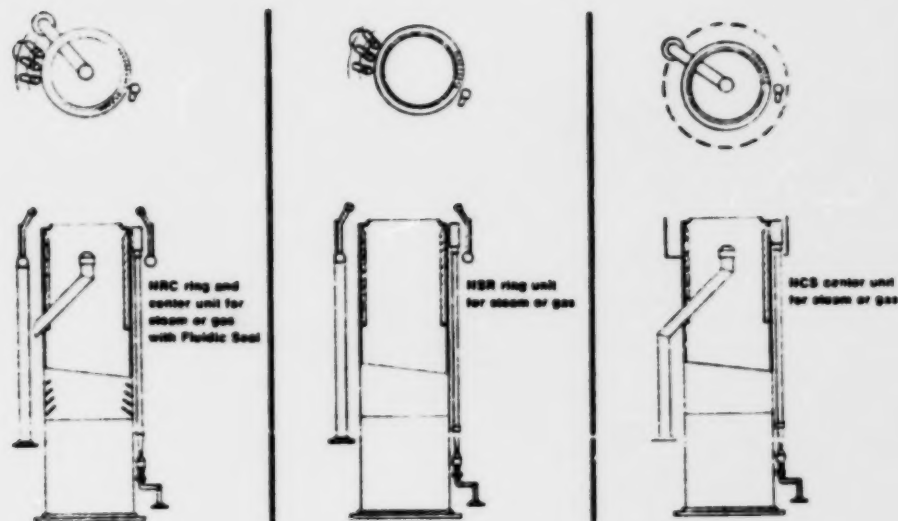
rates while the external jets are available at large flow rates. Figure 3-3 shows a schematic of National AirOil flare tips illustrating the different steam injection methods.

While these are the most common types of tips, there are several other mainly special purpose tips commercially available. A further modification of the steam injection tip is shown in Fig. 3-4. Here, an internal nozzle is used to inject both steam and air into the tip. The major disadvantage of this system is that a larger tip is needed because of the increased pressure drop. Under some circumstances, the gases may actually burn inside the tip. Figure 3-5 shows a tip using a Coanda effect of steam injection to achieve the required air gas mixture. While this method provides efficient mixing, the burning of the gas takes place inside the flare tip instead of outside or above as with the other tips. Burning inside the tip can drastically shorten the life of the tip. Figure 3-6 shows National AirOil's jet mix vortex tip. These can be used with relatively high pressure waste gases with little or no steam needed for smokless operations. Figure 3-7 shows the special purpose Indair flare tip which burns gases smokelessly without steam. It has limited use since it requires both high pressures and low pressure gas in the ratio of about three to one. Also its maximum turndown ratio is only about two. Other special purpose tips are available including endothermic tips that inject gas to raise the heat value of the waste stream and tips with added muffling for quieter flaring.

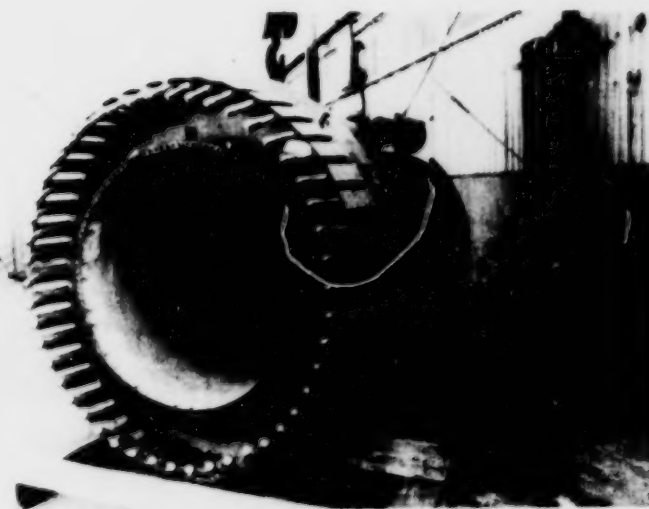
The rate of steam injection to the flare tip can be controlled manually or automatically. While automatic control is usually not mandatory, it is preferred because it reduces steam usage, greatly reduces the amount of smoking and minimizes noise. Automatic systems use flow measurement devices with ratio control on steam. Since the flow rate measurement cannot include the variables of degree of saturation and molecular weight, the ratio control is usually set for some average hydrocarbon composition. It is usually necessary to have a fixed quantity of steam flowing at all times to cool the distribution nozzles at the tip.

3.1.2 Gas Traps

To prevent air migration into the flare stack as a result of wind effects or density difference between air and flare gas, a continuous purge gas flow through the flare system is maintained. The system can be purged with natural gas, processed gas, inert gas or nitrogen. To reduce the amount of purge gas requirement and to keep air out of a flare system, gas trap devices are normally located in the stack directly under the flare tip. One type of gas trap commercially available is the molecular seal (Fig. 3-8). This type trap may not prevent air from getting in the stack as a result of gas cooling in the flare headers. Instrumentation systems are available to automatically increase the purge rate to prevent air from entering the stack during rapid gas cooling. A new development in gas traps is National AirOil's Fluidic Seal (Fig. 3-9). This seal weighs much less than a molecular seal and thus can be placed much closer to the flare tip.



a. Schematic of Ring or Center Unit for Steam



b. NAO 48-Inch Ring and Center Unit for Steam

Fig. 3-3 - Flare Tips Illustrating Ring and Center Steam Injection Units
(from National AirOil)

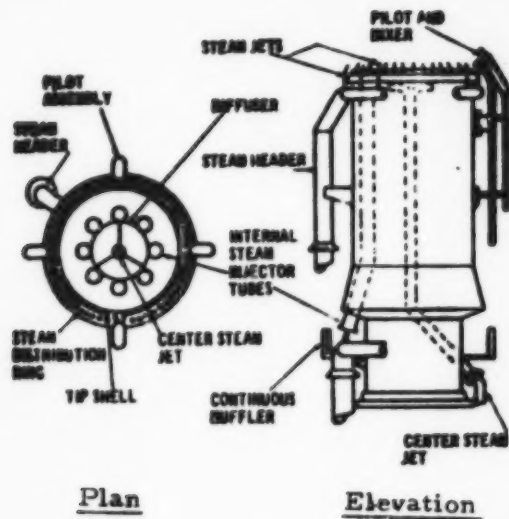


Fig. 3-4 - Detail of Internal Steam Injection System from John Zink Company

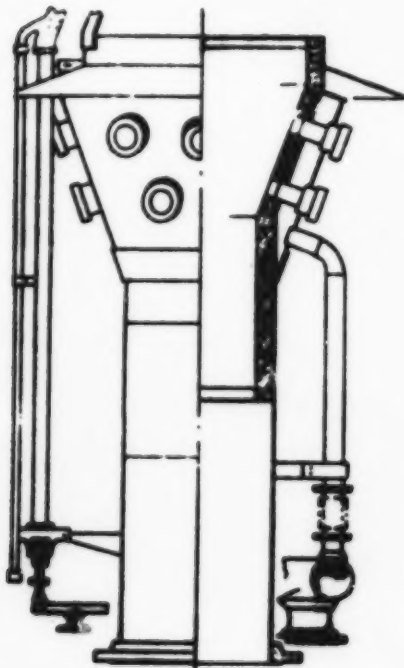


Fig. 3-5 - Coanda-Type Flare Tip from Flargas Engineering, Ltd.

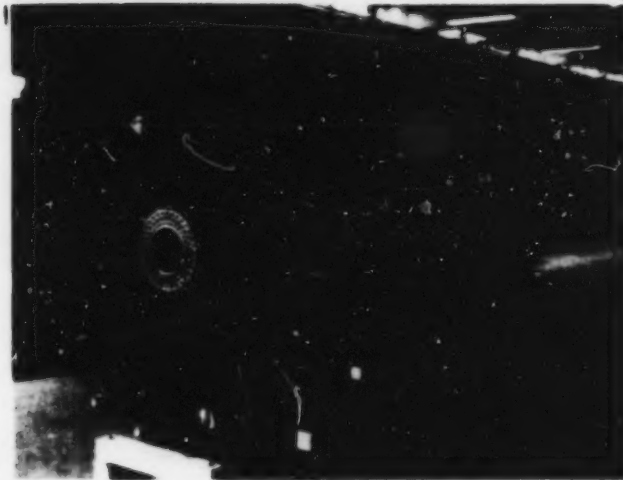


Fig. 3-6 - Jet Mix Vortex Flare Tip with Steam Assist
(from National AirOil)

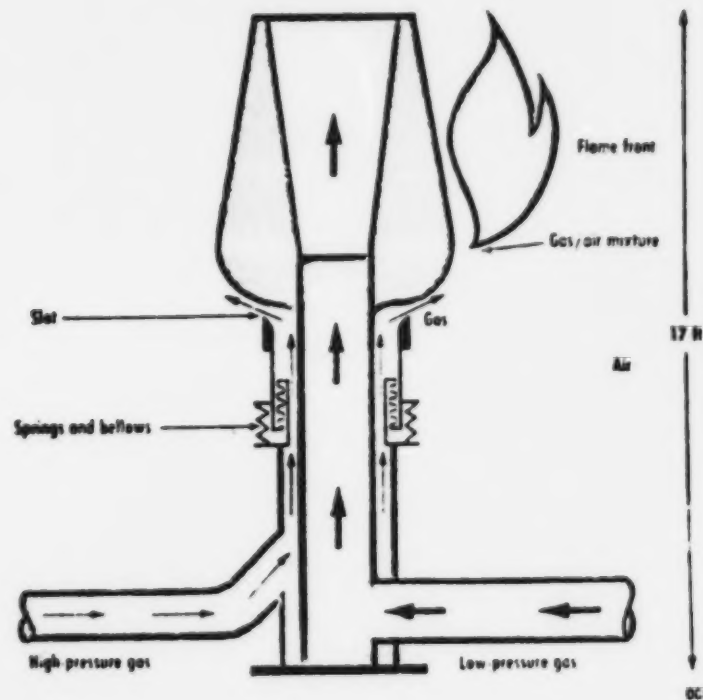
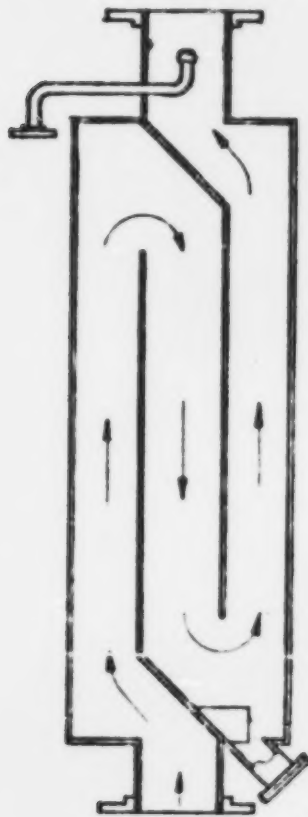


Fig. 3-7 - The Indair Flare Tip (from Oil and Gas Journal)

Outlet to Flare Burner

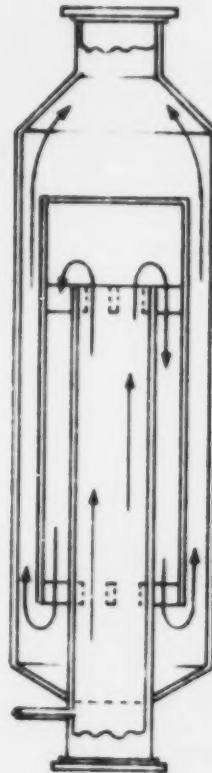


Clean-Out

Inlet from Flare Riser

National AirOil NDS Double Seal
(Patent applied for)

Outlet to Flare Burner



Inlet from Flare Riser

John Zink Molecular Seal
(U.S. 3,055,417)

Fig. 3-8 - Air Reentry Seals

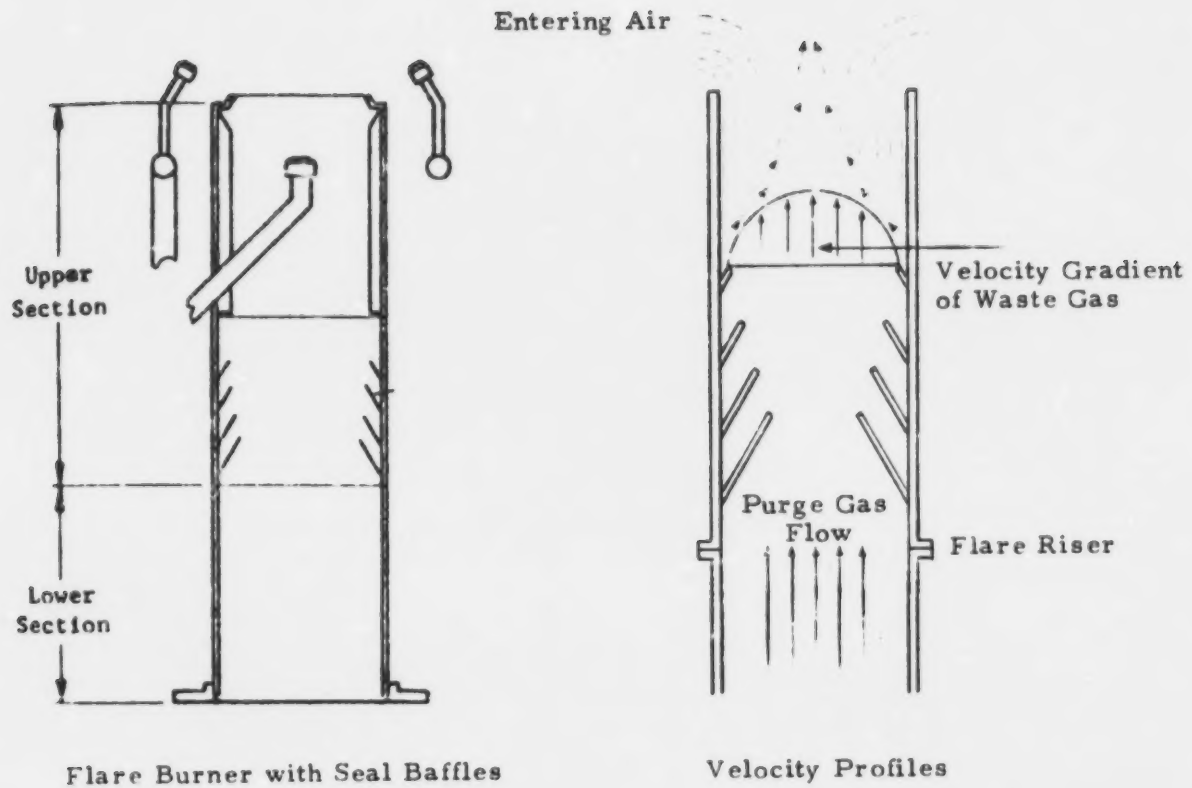


Fig. 3-9 - National AirOil Fluidic Seal

3.1.3 Pilot and Ignition System

The ignition mechanism for a flare installation usually consists of the pilot burners and the pilot burner igniters. The pilot burners serve to ignite the outflowing gases and to keep the gas burning. These pilots must provide a stable flame to ignite the flare gases, and in many cases, to keep them burning. To accomplish this more than one and usually three or four pilot burners are always used. The pilot burners are also sometimes provided with separate wind shields as shown in Fig. 3-10.

A separate system must be provided for the ignition of the pilot burner to safeguard against flare failure. The usual method used is to ignite a gas/air mixture in an ignition chamber by a spark. The flame front travels through an igniter tube to the pilot burner at the top of the flare. This system permits the igniter to be set up at a safe distance from the flare, up to 100 feet, and still ignite the pilots satisfactorily. Figure 3-11 shows one arrangement for the ignition system. The whole device is mounted on an ignition panel and set up in an accessible spot on the ground. The ignition panel must be explosion proof, have an unlimited life, and be insensitive to all weather conditions. On elevated flares, the pilot flame is usually not visible and an alarm system to indicate pilot flame failure is desirable. This is usually done by a thermocouple in the pilot burner flame. In the event of flame failure, the temperature drops and an alarm sounds.

3.1.4 The Stack and Its Support

Figure 3-12 shows the methods used to support the complete flare tower. These towers must be provided with a climbing ladder with a cage and landing on top for repair and maintenance purposes. These towers for refineries can range from 200 to 400 feet high. Flare towers with a proportion of length-to-diameter ratio less than 30 are usually constructed as self-supporting stacks; towers with a proportion $L/D < 100$ are supported with a set of guys, and when the proportion is $L/D > 100$, the towers are made with two or more sets of guys (Ref. 2). Self-supporting stacks are usually not built over 50 feet high because of the large and expensive foundation required (Ref. 4).

The guys need a large area for high stacks; that is why it is often preferred to build steel supports to which the stack is fastened. These are usually steel framework with a square cross section widened at the base. A triangular cross section, adopted from the modern television antennas, is more economical and has been used in several refineries (Ref. 8). The flare stack will expand because of the hot gas flow, and the supporting structure must be able to accommodate this expansion.

3.1.5 Water Seals, Flame Arrestors and Knockout Drums

Water seals and flame arrestors are used to prevent a flame front from entering the flare system. Flame arrestors have a tendency to plug and obstruct flow and are not capable of stopping a flame front in mixtures of air with hydrogen, acetylene, ethylene oxide and carbon disulfide; thus they are of little value (Ref. 1).

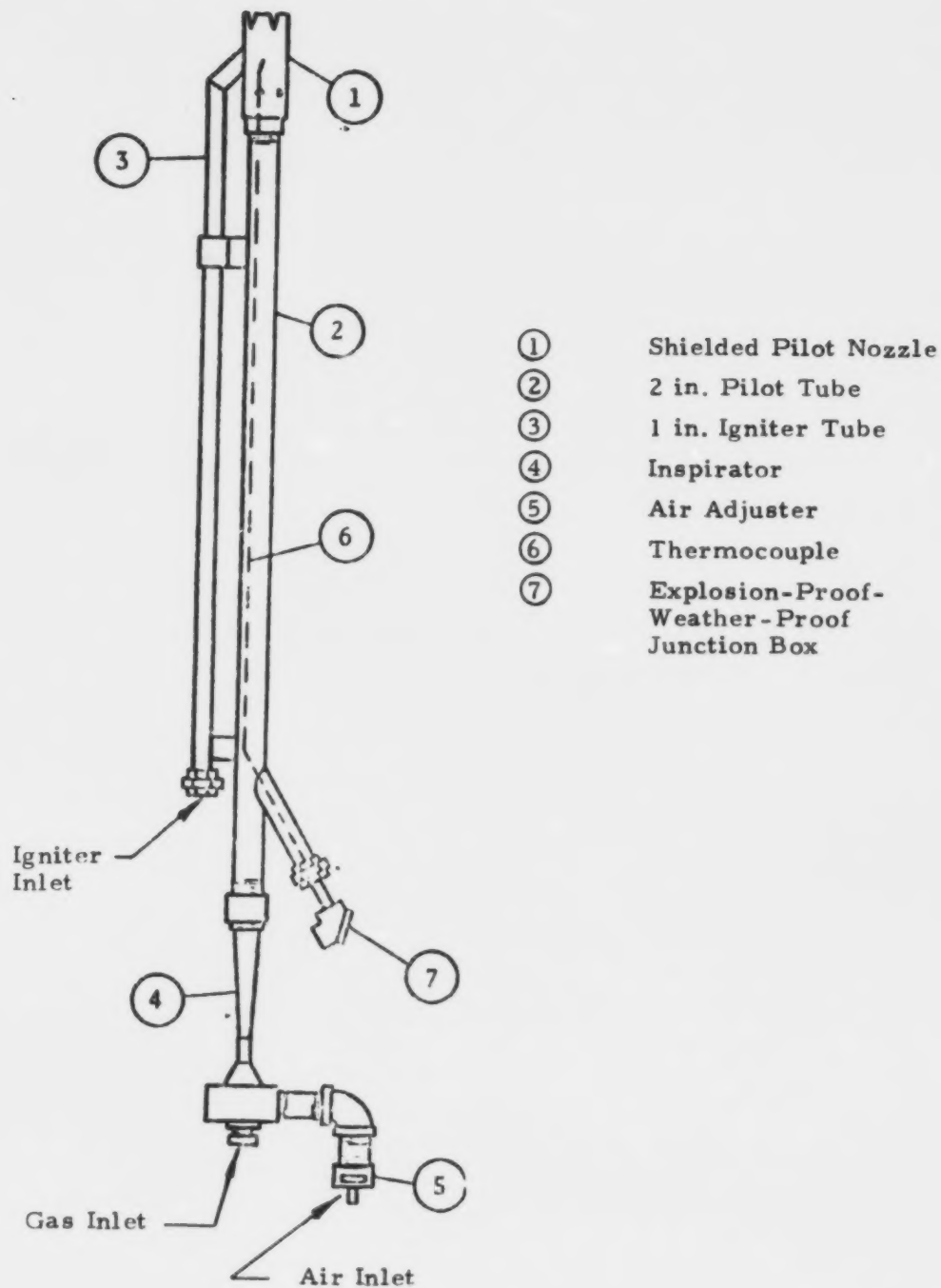


Fig. 3-10 - Flare Pilot Burner System

Description

- ① Mounting Plate - 18 x 36 in.
- ② Air Control Valve (1/2 in.)
- ③ Gas Control Valve (1/2 in.)
- ④ Gas Pressure Gage
- ⑤ Air Pressure Gage
- ⑥ Spark Sight Port
- ⑦ Spark Plug
- ⑧ Explosionproof Button (Push)
- ⑨ Transformer in Explosion-Proof-Weather-Proof Housing
- ⑩ Three-Way Valves

NOTE: Quantity of Item 10 will vary with number of pilots on flare.

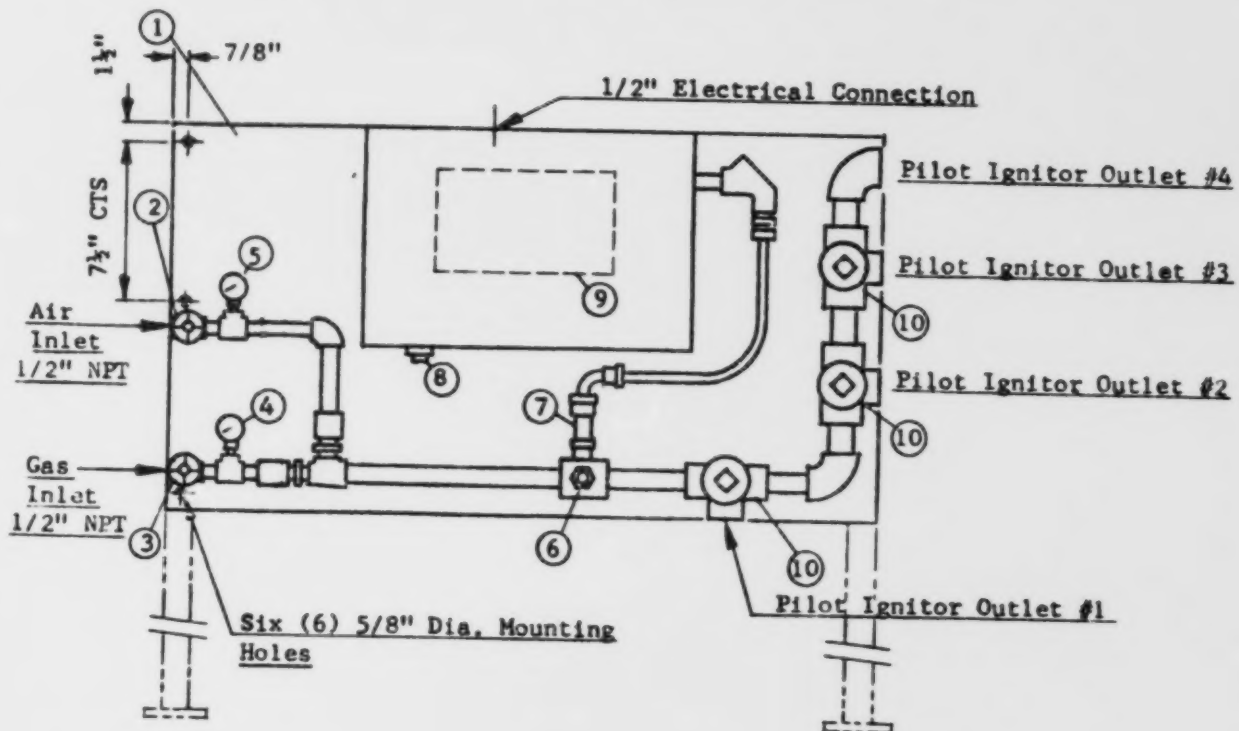


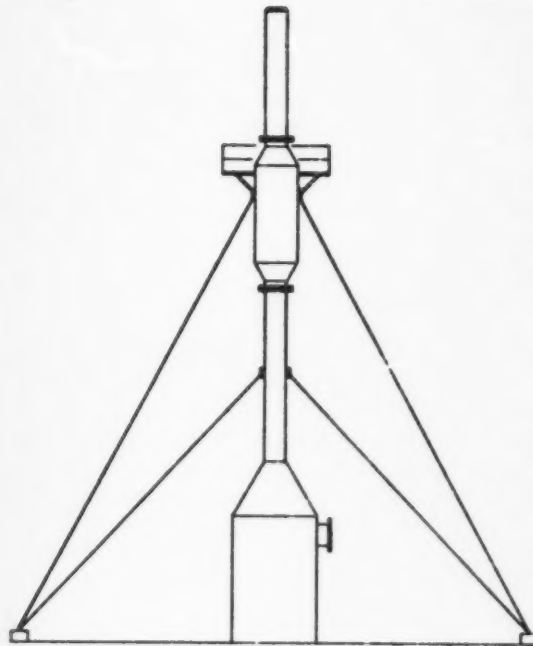
Fig. 3-11 - Flare Ignition System from National Air Oil



a. Self-Supporting



b. Flare with Support Tower



c. Flare with Guys

Fig. 3-12 - Flare Stack Supports

Water seals are used to prevent a flame front and air from entering the flare gas collection system. The weight of the water seal causes it to be located at or near grade and therefore the seal cannot be used to prevent air from entering the stack.

Knockout drums are located at or near the base of elevated flares to separate liquid from gases being burned. If the large liquid droplets are not removed, they could burn all the way to the ground. Designed for gases, flare lines can contain liquids from liquid expansion reliefs, liquid carried over from gas reliefs, and condensed vapors. The knockout drum is used to remove these liquids before the gases are flared. Water seals and knockout drums are found on most flare systems for safety reasons.

3.2 Ground Flares

A ground flare consists of a burner and auxiliaries, such as, a seal, pilot burner and igniter. Two types are found. One consists of conventional burners discharging horizontally with no enclosures. This flare must be installed in a large open area for safe operation and fire protection. If the ignition system fails this is not as capable in dispersing the gases as an elevated flare. For these reasons this type of ground flare has found only limited applications.

Ground flares may also consist of multiple burners enclosed within a refractory shell as in the recently developed "low level" flares (Figs. 3-13 and 3-14). The essential purpose of a low level flare is complete concealment of the flare flame as well as smokeless burning at a low noise level. The flared gases are connected by a manifold to a series of burner heads which discharge the gas into a refractory enclosure. Mixing of the gas and air is accomplished by a series of multi-jet nozzles. Combustion air is provided by the natural draft of the enclosure. Smokeless burning is obtained with little or no steam because of the turbulence and temperature of the burning zone due to the natural draft and the enclosure. The size of the enclosure depends upon the capacity of the flare but can become quite large. An enclosed ground flare with a capacity of 25,000 lb/hr has an enclosure 100 feet high and 20 feet in diameter (Ref. 9). This same capacity could be handled by an 8-inch diameter elevated flare.

The initial costs of an enclosed ground flare usually limits their capacity to just a portion of a plant's emergency dump rates. However, the ground flare can be designed to handle most flare occurrences and the remaining large releases can be diverted to an elevated flare. Figure 3-15 is a schematic showing how such a system might work. This type of integrated flare system is now becoming common especially in populated areas.

3.3 Forced Draft Flares

The forced draft flare uses air provided by a blower to supply primary air and turbulence necessary to provide smokeless burning of relief gases without the use of steam. Figure 3-16 shows two common designs

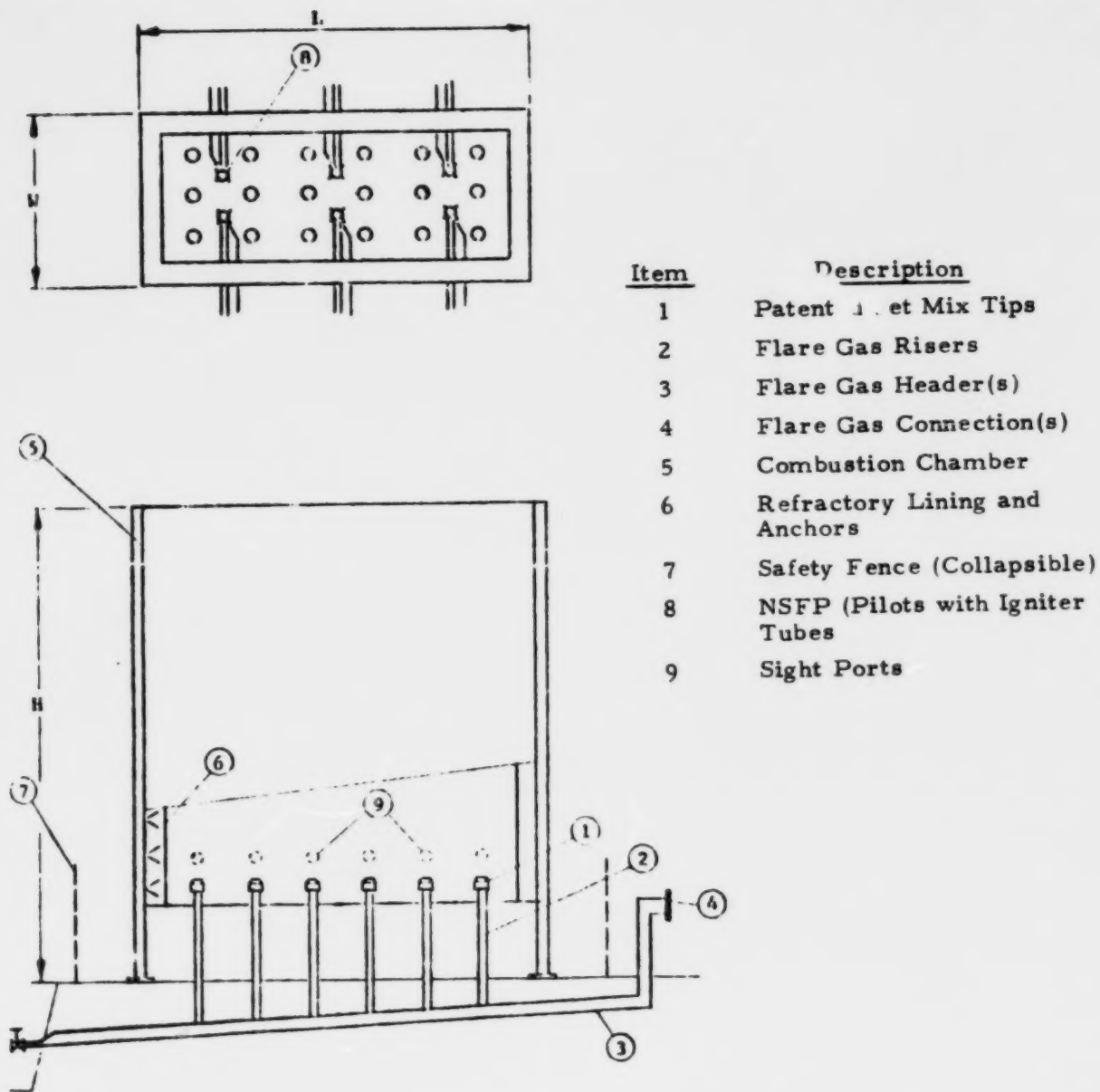


Fig. 3-13 - Ground Flare (from National AirOil Burner Company)

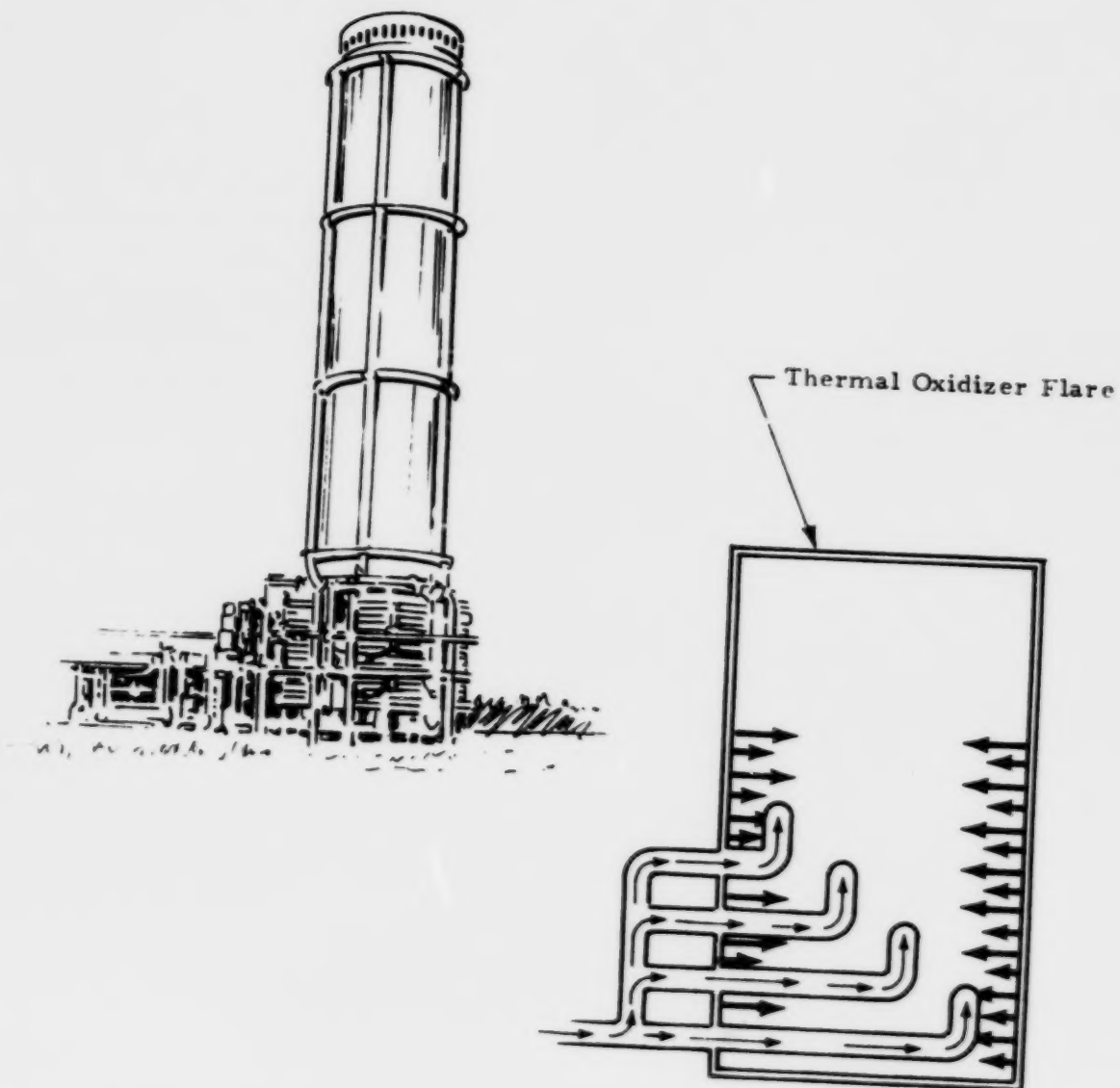


Fig. 3-14 - Ground Flare ZTOF from John Zink Company

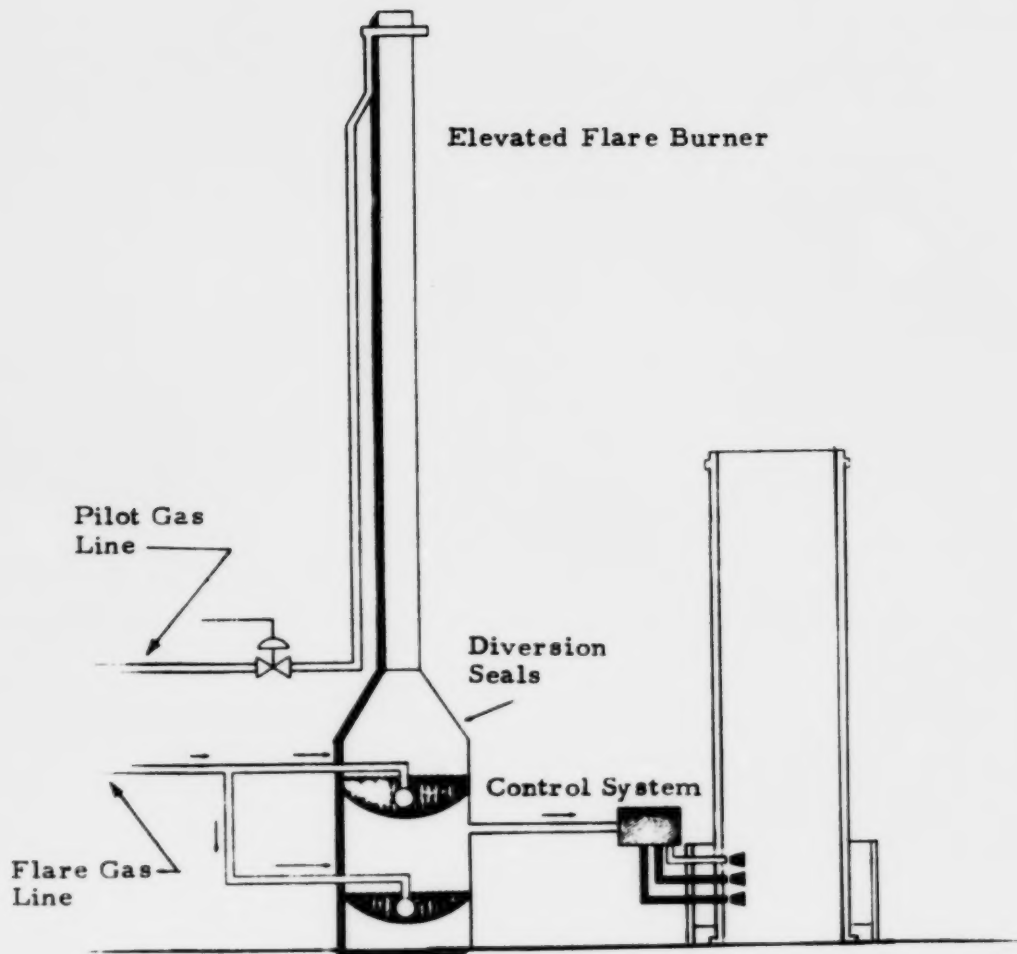


Fig. 3-15 - Ground Flare and Elevated Flare Connected by a Double Stage Water Seal

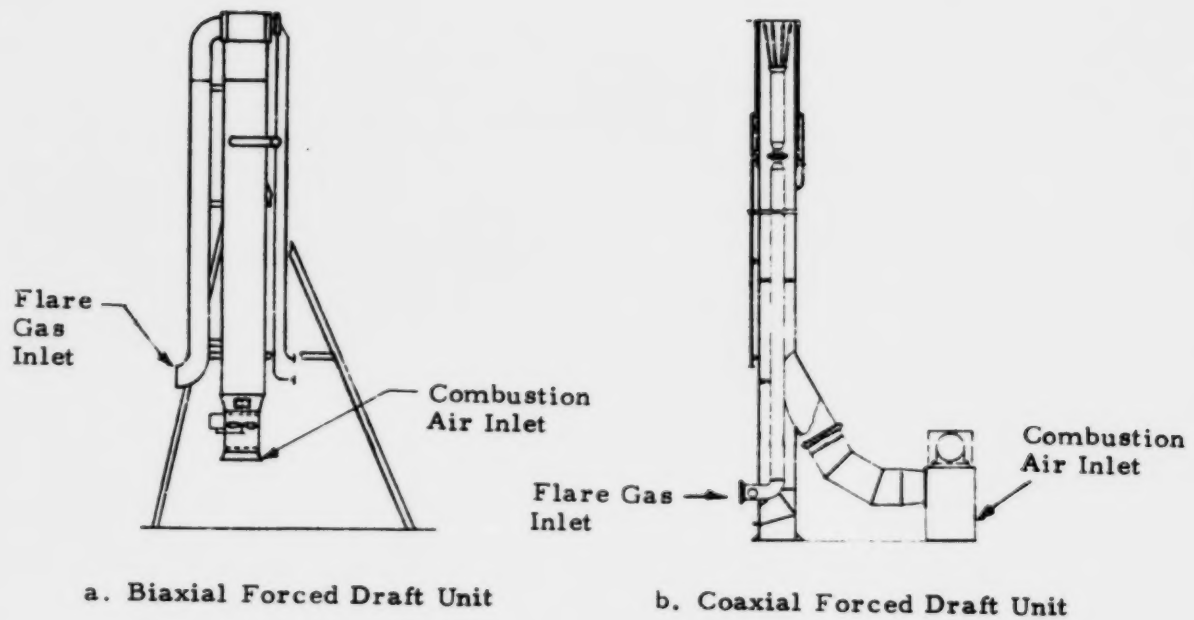


Fig. 3-16 - Two Designs for Forced Draft Flare Systems

of forced draft flares. This type of flare combines smokeless burning with low operating cost and reliability because only pilot gas and electricity are required. The flame is also stiffer and, because of the forced draft, is less affected by the wind.

However, this flare also has a high initial cost. The cost can run two to three times the cost of a conventional flare, mainly since two stacks are necessary to keep the air and gas separated until they are mixed and ignited at the tip. A blower flare should have an automatic air turndown device to prevent excess air from quenching the flame and creating smoke if the flare gas rate is reduced. Variable speed blowers or baffles coupled to flow sensing devices have been used on these flares to extend their turndown ratio. Because of costs and turndown ratio limitations, this flare has been used mostly in special applications. It has been used mainly to provide smokeless burning where steam is not available. It has also been used in tankage transfer and venting and in conjunction with a smoking elevated flare to provide smokeless burning for day-to-day flaring.

3.4 Comparative Costs of Flare Systems

The capital and operating costs for a given flare system depend on many factors such as the availability of steam, the size of the flare, the composition of the waste gas and the frequency of flaring. Each installation is a special problem, the economics of which must be solved for the specific case.

Vanderlinde (Ref. 9) estimated the relative cost of equipment used in the smokeless flare systems. Equipment costs include a guyed stack, ignition piping, pilot piping, the burner ring and accessories. As shown in Table 3-1 he found that the relative cost of smokeless flare systems was not stack diameter dependent. On the other hand, relative cost of the equipment for a forced air system is diameter dependent, because a stack

Table 3-1

RELATIVE COSTS OF FLARE SYSTEMS

<u>Type of Flare</u>	<u>Equipment Costs</u>	
	12-in. Diam.	24-in. Diam.
Smoking		
Standard Tip	1.00	1.00
Smokeless		
Steam Tip	1.25	1.25
Gas Tip	1.30	1.30
Water Tip	1.20	1.20
Forced Draft	2.80	3.38

within a stack is actually being purchased. Low level enclosed flares with an equivalent capacity of an elevated flare can be as much as ten times more costly (Ref. 10). For this reason the enclosed flare is only designed to handle the smaller day-to-day flare occurrences.

Typical costs for the flare system of a 350,000 bbl/day refinery would be of the order of \$750,000. This cost includes \$500,000 for equipment for two elevated and one enclosed low level flare. Of the \$500,000 for equipment, \$300,000 would be for the low level flare. Another \$250,000 would be needed for the waste gas collection system (Ref. 11).

SECTION IV

FLARE DESIGN CRITERIA

The complete design specification of a given flare system for use in safety relief is highly specialized and requires close cooperation between the buyer and manufacturer. In addition, some factors affecting design are determined by the type of equipment used; in these cases in which the equipment is proprietary, design information is not readily available. Nevertheless, a number of design guidelines have been published in recent years which serve as general guidelines for equipment sizing and estimation of plant space requirements. These are given as Refs. 2, 4, 5, 12, 13 and 14.

The objective of this section is to examine the available design and sizing criteria in order to describe the state of the art of flare design. Emphasis is placed upon calculations which affect emissions of heat, light, noise, smoke, particulates and chemicals and the dispersion of gases and particulates. Auxiliary equipment such as drums, seals and flame arrestors are also discussed in this section.

As noted previously, flaring is intended primarily as a safety measure for disposing of large quantities of gases primarily during plant emergencies such as fires, electrical failure, failure of cooling water supplies and other utilities, equipment overpressure, compressor failure, or problems which may be encountered during start-up. Less frequent applications during which large quantities of gas may be sent to flare can include the disposal of "off-spec" product and excess product which cannot be stored. Flows are typically intermittent with very large flow rates during major upsets in the range of several hundred thousand pounds per hour. Flare systems are therefore required to accommodate a very large "turndown" range of flows. Total capacity and turndown range are normally the deciding factors in selecting the applicable flare system. The type of flare used will depend to a lesser extent upon the type of materials being sent to flare, the flare location and available utilities.

4.1 Selection of Applicable Flare System

In general, flare systems are divided into two broad categories, ground flares and elevated flares which discharge the waste stream at some distance above ground level. Ground flares may consist either of conventional flare burners discharging horizontally at or near ground level or of distributed burners enclosed within a refractory shell, as in the more recently developed "low-level" flares. Low-level flares have a relatively large diameter which reduces discharge velocity and, thus, sonic emissions. Enclosing the flame reduces light and thermal emissions. Air for the low-level flare is normally provided by natural draft; for this reason, and because of the time required to heat the refractory, the low level flare design has a more sluggish response to sudden upsets than elevated flares. Low-level flares are normally used for minor upsets or for small, steady state flows with an elevated flare of conventional design used to

accommodate full-scale emergency upsets. Horizontal discharge flares are essentially elevated flare systems discharging at ground level and have a somewhat limited application because of the large open area of a minimum of 1500 ft² required for safe operation. Heat and sound emissions and other reasons for this requirement will be discussed later in this section. Flares discharging at ground level are generally considered unsuitable for flaring gases which may be odorous, noxious, or toxic in nature or for flaring gases which may produce compounds having these properties as intermediates or final combustion products.

For general purposes, in which a variety of flow ranges and compositions may be encountered, the elevated flare is more common. Elevated flares (and elevated flare burners discharging at ground level) provide air for combustion either by forced draft or by diffusion of air into the fuel beyond the point of ignition and discharge to the atmosphere. Burning the waste stream by means of natural convection (as in a ground flare) or by forced convection results in a premixed flame, while burning without added air results in a diffusion flame.

Typically, elevated flares used for large waste systems are diffusion burning with steam added to reduce smoking. The application of forced draft flares is limited to smaller, steady flows such as in tankage transfer storage tanks, and for use in plant facilities where steam is not available. Typical maximum flare capacity ranges are

Type	Capacity (1000 lb/hr)
Low Level Flare	80 - 100
Elevated, Diffusion Flame	1000 - 2000
Elevated, Forced Draft	100

The maximum capacity ranges were obtained from conversations with flare vendors and should be used as a guideline only. Actual capacity will vary somewhat with the type of gas being flared and other requirements.

A number of specialized flare burner designs are also available to accommodate high pressure side streams. Endothermic flares are also available to support combustion of gases which are too lean or have too little heat content to support a flame. Endothermic flaring may be accomplished using either auxiliary heaters or an "assist" fuel gas.

4.2 Flammability Limits and Flame Stability

Whether or not a given waste stream will support a flame is normally determined experimentally, but methods are available for estimating flammability limits (Ref. 1). In some cases, flammable mixtures may not release sufficient combustion heat to maintain the flame at a stable temperature. The lower (net) heating value required to support a flame

varies somewhat with flare burner design; larger flames require a higher heating value fuel than would be required for combustion in a distributed burner. A lower heating value of 200 - 250 Btu/scf is normally considered adequate for flaring in large elevated flares. Heating values for gases normally flared may be calculated using standard methods or obtained from furnace handbooks such as Ref. 1. Endothermic flare systems with auxiliary heaters or assist gas addition to increase heat content may sometimes be used in flaring low heating value gases.

Flame instability may occur when the discharge velocity exceeds or falls below the burning velocity. In the case of either premixed or diffusion flames, an instability may occur when the discharge velocity exceeds the flame velocity leading to a lifted flame in which mixing of the fuel and dilution with air must precede the re-ignition of the flame. This condition is known as "blowoff" (Ref. 12). The flame itself may even blow out if the discharge velocity greatly exceeds the flame velocity. The opposite condition in which the gas velocity falls below the burning velocity results in a condition known as "flashback."

Maximum discharge velocity, and therefore flare burner diameter is fixed between these upper and lower limits of "blowoff" and "flashback" by the burning rate of the fuel. In practice, in order to minimize capital costs and increase the flare throughput, most flares are designed for maximum throughput based on the maximum allowable pressure drop. Flame holders are used to maintain flame stability and extend these stability limits. These are of proprietary design, typically consisting of a perforated ring at the circumference of the flare tip. The gas flow is divided by the ring into small streams thereby increasing air-gas mixing in a portion of the gas stream (Ref. 9). Large pilot flames can also be used to stabilize the flame. Small amounts of gas having a relatively high burning rate, such as hydrogen, may be added to the flared stream in order to widen the stability limits (Ref. 12). The instability at the lower velocity limit can be avoided by the use of a purge gas which may be either a flammable or inert gas. The low flow instability is not a problem when vapor purging is employed, for safety reasons, to prevent the formation of flammable mixtures in the flare stack at low or no flow. Vapor purging is discussed further in Section 4.4.2.

Flare diameters are normally sized, within the maximum allowable pressure drop, to provide vapor velocities at maximum throughput of about 20% of the sonic velocity in the gas (Refs. 12 through 14). There is evidence that flame stability can be maintained at Mach numbers up to 0.5 (Ref. 12).

Exact analysis of flame stability appears to be beyond the state of the art for flare design. It is doubtful whether a model exists for turbulent flames which is satisfactory for estimation of the burning velocity. It has been determined (Ref. 15) that the burning rate is several orders of magnitude lower than theoretical even for highly efficient combustion equipment

such as gas-turbine combustors. It is probable that mixing controls the burning velocity in flare systems. Recent flare tip designs for smokeless burning have included tangential discharge of either the flare stream or steam to stabilize the flame at high discharge velocities, but such developments appear to be based on empirical observation rather than analysis.

4.3 Flare Emissions

Flare emissions include chemicals and particulates, thermal and visible radiation and noise. It is the purpose of this section to discuss the probable causes of emissions, the state of the art in quantifying and controlling these emissions, and the extent to which flare design has been affected.

4.3.1 Thermal Emissions and Luminosity

Emission of heat from flares will be discussed in detail in Section 4.4.9. As in the case of thermal radiation, it is probable that most of the visible radiation is the result of radiation from hot carbon particles. Electronic transitions, such as in the formation and recombination of certain radicals: CH, C₂, HCO, NH, and NH₂ are also accompanied by emission in the visible and near ultraviolet, but probably contributes only a small fraction of the total luminous radiation (Ref. 16). The distribution of radiation frequencies from hot carbon particles is predicted from Planck's radiation law and requires a knowledge of the flame temperature. For practical use, a close approximation is given by Wien's law (Ref. 16) for $\lambda T < 0.2$ cm-deg:

$$I_{\lambda} = 2E_{\lambda} A C_1 \lambda^{-5} e^{-C_2/\lambda T} d\lambda \quad (4.1)$$

where

- λ = radiation wavelength, cm
- I_{λ} = radiation intensity between λ and $\lambda + d\lambda$, W/cm² (per unit surface of the emitter)
- E_{λ} = the emissivity at λ (for blackbody radiation, $E_{\lambda} = 1$ for all values of λ)
- A = the surface area of the emitter, cm²
- T = absolute temperature, °K
- C_1 = first radiation constant
= 0.588×10^{-12} W/cm²
- C_2 = second radiation constant
= 1.438 cm-°K

The radiation maximum calculated from Wien's law allows an estimation of the temperature dependence of the fraction of visible light emitted:

$$\lambda_m T = 0.289 \text{ cm}^\circ\text{K} \quad (4.2)$$

thus, the maximum wavelength depends strongly on temperature. Since the intensity at this wavelength is directly proportional to area, it follows that control of the emission of visible light is closely related to the concentration and surface area of particulates and the flame temperature. For hotter flames, the radiation is shifted toward the visible portion of the spectrum. In flaring practice therefore, injection of steam to reduce carbon formation decreases both the flame temperature and the area for emissions and therefore the emission of visible light. Increasing the steam beyond the amount needed to prevent soot formation causes a further reduction in luminosity (Ref. 12). Smokeless flaring achieved by pre-mix burning or multijet burning should result in a higher flame temperature and a higher luminosity than would be observed during steam injection.

No design modification has been developed which will completely eliminate luminosity, and in practice the tendency in populated areas has been to enclose the flame at ground level. This requires a special type of ground flare and has several disadvantages and limitations. Such flares are essentially ground level distributed burners (to reduce flame height) enclosed within a refractory shield to reduce thermal and light emissions. Air is supplied by a natural draft, therefore turndown is limited and an initial time lag between initial fuel firing and air supply is inevitable (Ref. 17). Capital costs for these units are higher than those for conventional flares of the same capacity by about a factor of 10, and maintenance costs are also higher. Because of the relatively low discharge height, such flares are not suitable for flaring toxic or hazardous gases. Because of the limited turndown and inability to respond to sudden flow changes, low-level flares are more suitable for flaring when normal flows are continuous. Elevated flares are recommended for use in addition to the ground flare whenever protection against sudden upsets is required.

4.3.2 Noise Emission

Sonic emissions from flares consist of contributions from high frequency jet noise and combustion noise which is of relatively low frequency (Refs. 9 and 18). Jet noise is caused by a fluid passing through a constriction and is directly proportional to the pressure drop (Ref. 9) or (equivalently) roughly proportional to the square of the mass flow rate through a nozzle of fixed diameter (Refs. 18 and 19) according to the behavior expected for highly turbulent flow. The intensity of jet noise is also a function of the fluid properties. Combustion noise is a function of flame turbulence and is directly proportional to the amount of air mixed with the flare gas (Ref. 9).

Jet noise in flare systems results mostly from high pressure steam injection to achieve smokeless flaring, and this is the major source of the noise problem. The major steps taken to curb high frequency noise emission have involved re-designing steam injectors to reduce the steam exit velocity and the use of peripheral mufflers (shrouds) to prevent both

the direct sound radiation and reflection from the flare stack (Refs. 19 and 20). A multiport nozzle design reported by Chevron (Ref. 19) resulted in a 96% reduction (by 14 decibels) in the sound power radiated to the steam-air injection system. The major reduction was in the range 1000 to 2000 Hz with little reduction of low frequency combustion roar (290 Hz <). A Coanda-principle injector developed by Flaregas (Ref. 21) reduced high frequency noise by about 7 - 16 dBA 150 feet from the flare with steam rates varying from less than 1 to about 20 tons per hour below the sound levels for center steam and external jet injection. The Coanda effect injector had little effect on low frequency combustion noise less than about 250 Hz.

High frequency jet noise resulting from steam injection has been the subject of most design attention (Ref. 20) because of its higher intensity levels, while the problem of steady combustion noise has not yet been dealt with effectively (Ref. 18). Injection of steam for smokeless operation increases turbulence intensity, causes the flame to become shorter and stiffer and increases the relatively low frequency combustion noise. The only available solution to the low frequency combustion noise problem has been the use of low level enclosed ground flares. The enclosed ground flare both damps the noise and allows the burners to be fine tuned in order to reduce noise. If combustion noise is objectionable, moderate and most frequent releases can be burned at ground level, with an auxiliary elevated flare for full-scale venting.

Both combustion and jet noise are functions of the individual flare tip design. However, flare vendors indicate that scaling of various sizes and capacities is possible using standard procedures (Ref. 20) and reference sound level data for most flare burners is typically available from the manufacturer. An experimental correlation for estimation of jet noise is also available (Ref. 22).

For design purposes, in order to determine whether jet noise must be reduced by shrouding or other means, other sound sources in the area must also be considered (Ref. 23). Variation of sound intensity with distance from the source is obtained using an equation for hemispherical spreading (Ref. 12):

$$L_p = L_{100} - 20 \log_{10}(r/100) \quad (4.3)$$

where

$$\begin{aligned} L_p &= \text{sound pressure at a distance } r, \text{ dB} \\ L_{100} &= \text{reference sound pressure at a distance} \\ &\quad \text{of 100 feet, dB} \\ r &= \text{distance from sound source, ft.} \end{aligned}$$

For multiple sources, the following inequality must be satisfied (Ref. 24):

$$\frac{C_1}{T_1} + \frac{C_2}{T_2} + \dots + \frac{C_n}{T_n} < 1 \quad (4.4)$$

where

$$\begin{aligned} C_n &= \text{exposure duration} \\ T_n &= \text{allowable exposure duration} \end{aligned}$$

Present and proposed regulations limiting noise exposure are summarized below (Ref. 24)

Exposure per Day (hr)	Current OSHA Regulation (dBA)	Proposed NIOSH Regulation (dBA)
8.0	90	85
4.0	99	90
2.0	100	95
1.0	105	100
0.5	110	105
0.25	119	110

Very serious low frequency noise problems can result from improperly designed water seals which may vibrate at frequency levels (Ref. 18):

$$\tau_a \cong 0.31 D/H^{1/2} \quad (4.5)$$

$$\tau_s \cong 0.149 D/H^{1/2} \quad (4.6)$$

where

τ_a = period of asymmetric pulsation, sec

τ_s = period of symmetric pulsation, sec

D, H = diameter and height of seal drum, respectively, ft.

To alleviate this problem, water seal downcomers are usually terminated in slotted tips of irregular length, and a perforated baffle plate is installed at or very slightly below the equilibrium liquid level to increase damping. A smaller and less submerged auxiliary relief pipe may also be installed (Ref. 18).

Pulsations from water seals and from low flow instability can be avoided if a lower linear velocity of 1 to 3 ft/sec is maintained in the flare stack at all times. This figure is based on observations of low flow instability in larger flare systems (Ref. 18).

Low level flares reduce combustion noise by about 10 dB (Ref. 20). High frequency jet noise is not a problem with this type of flare because of the distributed burner design and the absence of steam jets. However, these flares are subject to poorly understood "combustion driven" pulsation which may cause low frequency vibrations (Ref. 18).

4.3.3 Smoke and Particulate Emissions

Almost all flames of organic gases and vapors are luminous due to incandescent carbon particles formed in their flames; exceptions are carbon monoxide, methyl alcohol, formaldehyde, formic acid, carbon disulphide, and cyanogen (Ref. 16). Under certain conditions these particles are released from luminous flames as smoke. The tendency for smoke production is related to: (1) the quantity and distribution of oxygen in the combustion zone, and (2) the type of gas being burned.

The most critical determinant of smoke production is the amount and distribution of oxygen in the combustion zone. For complete combustion of a product, a stoichiometric quantity of oxygen is required in the burning zone. For smokeless combustion to take place a portion of the stoichiometric quantity of air must be evenly distributed in the primary mixing zone. The remaining air required to complete the combustion process is induced into the flame through aspiration and thermal draft effects. This primary air must be well mixed with the gas prior to flame ignition or soot will escape from the flame due to incomplete oxidation taking place (Ref. 9).

The second factor influencing carbon formation is the molecular structure of the gases burned. The carbon to hydrogen ratio is one of the principal factors controlling the tendency to carbon formation. The structure of the molecule is also important, thus branched chain paraffins smoke more readily than the corresponding normal isomers. The more highly branched the paraffin, the greater the tendency to smoke (Ref. 25).

In forming soot or smoke in flames one starts with a small hydrocarbon or organic molecule and ends with a relatively large particle containing many thousands of atoms and a much higher carbon-to-hydrogen ratio. Thus there must be both dehydrogenation and polymerization side reactions involved. The exact route from small hydrocarbons to large soot particles is, however, uncertain (Ref. 25). Once soot is formed, it is either consumed in the flame or emitted from the flame. Soot particles emitted from the flame large enough to be visible can be detected as smoke. Studies of particulate emissions from flames have thus far been concerned with visible emissions. It is possible that a luminous flame can appear smokeless and still be emitting particles too small to be visible. Thus making a flame smokeless will eliminate visible emissions but could cause an increase in very small particle emissions. These fine particulates would be incorporated into the plume by viscous drag forces and would disperse into the atmosphere. Particulates are removed from the atmosphere by adsorption surfaces (i.e., vegetation, pavement buildings, etc.). The mechanisms which cause adsorption are gravitational settling, diffusion down to and impacting with the surface and precipitation scavenging.

The carbon formed in flames generally contains at least one percent by weight of hydrogen. The deposited carbon appears to consist of roughly spherical particles with diameters varying from 100 to 2000 Å and most commonly between 100 and 500 Å. The smallest particles are found in luminous but nonsooting flames while the largest are obtained in heavily sooting flames (Ref. 26).

For flares a smokeless flame can be obtained when an adequate amount of air is mixed sufficiently with the fuel so that it burns completely before side reactions can cause smoke. In order to get good mixing of oxygen or air with a combustible material, an expenditure of energy is required. This energy may be provided by the flare gas stream itself through pressure reduction and/or thermal draft; or it may be provided from an external source, such as steam injection, power gas assist or a blower fan. The usual method to achieve a smokeless flame in a flare is to introduce steam into the combustion zone to promote combustion and retard the carbon forming reactions. This tends to retard smoke formation in three ways: (1) the injection of the steam can be used to inspirate air and provide turbulence to aid in the mixing of the fuel and air; (2) the steam reacts with the fuel to form oxygenated compounds that burn readily and also lowers the temperature of the unburnt gases retarding thermal cracking; and (3) the steam dilutes the fuel and reduces the partial pressure of the fuel which reduces the carbon formation in diffusion flames.

Steam is injected either through a center spray nozzle or a circumferential steam ring, or both. Required steam-to-fuel ratios are empirical and vary with the type of material being flared. For hydrocarbons, a design equation from Tan (Ref. 13) is available based on experimental data (Ref. 12):

$$W_{\text{steam}} = W_{\text{HC}} (0.68 - 10.8/M) \quad (4.7)$$

where

$$\begin{aligned} W_{\text{HC}} &= \text{hydrocarbon flow rate, lb/hr} \\ W_{\text{steam}} &= \text{steam flow rate, lb/hr} \\ M &= \text{average molecular weight of the flared stream.} \end{aligned}$$

The equation arbitrarily assumes a constant steam-to-hydrocarbon ratio.

Experimental studies have not reflected such a simple dependence of smoke formation on molecular weight. The most significant parameter for hydrocarbons appears to be the ratio of carbon-to-hydrogen, but other factors must also be considered such as the type of hydrocarbon being burned, the temperature of the combustion zone and the quantity and distribution of oxygen in the combustion zone.

In flare systems utilizing steam for reduction of particulate emissions, steam requirements are based on some fraction of the maximum design capacity. Discussions with flare vendors indicate a typical basis of about 50% design capacity. Thus, only moderate relief rates will be

burned smokelessly. Economics, not design factors, limit the smokeless capacity of a flare. It is usually not feasible to maintain enough steam capacity to handle very large flare loadings. The practical limit of smokeless burning is about 300,000 lb/hr (Ref. 27).

The minimum amount of steam required produces a luminous flame with no smoke. Increasing the amount of steam injection further decreases the luminosity of the flame. An injection of an excessive amount of steam causes the flame to disappear completely and be replaced with a steam plume. Too little steam results in black smoke which is objectionable and excessive steam produces an invisible emission of unburned hydrocarbons (Ref. 5). With automatic steam control in flare installations, the use of an excessive amount of steam and the emission of unburned hydrocarbons is greatly reduced.

Other methods used to achieve smokeless burning in flares include the use of water spray rather than steam, blowers to provide a forced air draft, distributed flame or multijet burners, and low level ground flares which rely on natural draft to provide air. Water sprayed is 50% less efficient than steam and is frequently completely ineffective in providing smokeless operation when the flame is tilted away from the injection ring by a strong wind. Other problems with water spray injection include a limited turndown rate of about 0.8 to 1, freezing in cold weather, and quenching of the flame at low vapor relief rates.

Water spray injection has been applied successfully in special applications such as with ground flares (Ref. 8) but is not recommended in applications where air pollution is a problem (Ref. 5).

Smokeless flaring by means of multijet or distributed burner designs pose safety problems inherent with throttling the discharge stream. Standby flares of conventional design are usually considered necessary to accommodate emergency upsets. Low-level ground flares are essentially distributed burners at ground level and are sometimes useful in reducing smoke emissions (Ref. 29). Other distributed burner designs include a multiflare in which high and low pressure streams are collected in segregated piping systems and discharged at the flare tip through nozzles of different design. This technique is intended to utilize the energy of the high pressure waste stream to achieve increased mixing.

Forced draft flares use a blower to provide air for smokeless burning. For operating safety, air and fuel are injected in concentric stacks and mixed in a chamber near the flare tip. Premixing limits the turndown rate unless special blower control is provided. Forced draft flares are less popular than conventional elevated flares because of the high initial and operating costs and limited turndown and are normally used only when flare location prevents steam or water injection for smoke control.

Because of the intended use of flare systems as emergency control devices, particulates are not monitored. Thus, there is no experimental

basis for choosing between steam (or water) and air injection for particulate control. Kinetic measurements on soot formation and oxidation in small flames (Ref. 16) indicate that the net rate of formation is kinetically controlled with a higher activation energy for the oxidation. On this basis, air addition would appear to be preferable.

4.3.4 Chemical Emissions

Chemical emissions from flares may result from unburned fuel and partial or complete oxidation products. Flare discharge rates are extremely high; at the emergency release rate, burning rates on the order of 10^9 Btu/hr are typical (Ref. 30), with the reaction distributed over flame lengths of several hundred feet.

Discharge flows are typically highly turbulent at the tip of the flare burner; literature design methods such as given by Tan (Ref. 13), Kent (Ref. 14) and API RP 521 (Ref. 12) recommend the use of Mach 0.2 for sizing calculations. Conversations with flare vendors suggest that this figure may be low by 30% or more. Flame "holders" installed at the tip of conventional burners allow velocities greater than Mach 0.2 before flame lift-off occurs. It has been suggested that quenching of the combustion by turbulent mixing with the cold ambient air may result in the formation of partial oxidation products and unburned hydrocarbons. Data of Sussman et al., (Ref. 31) suggest that combustion of hydrocarbons in the steam-inspired type of elevated flares may be incomplete. The results of a field test on an elevated flare with steam inspiration indicated that hydrocarbon and carbon monoxide emissions from a flare can be much greater than those from a properly operated refinery boiler or furnace where the CO emission is negligible and hydrocarbon emissions are 0.14 lb/bbl of fuel burned (Ref. 58) Sussman et al., reported the results in the form of ratios:

$$\begin{aligned}\text{CO: hydrocarbons} &= 2,100:1 \\ \text{CO}_2: \text{CO} &= 243:1\end{aligned}$$

Irritants (Ref. 32) such as aldehydes and other partial oxidation products are also possible if combustion is incomplete. Aldehydes, CO and other partially oxidized hydrocarbons have been established (Refs. 5 and 16) as intermediates in hydrocarbon combustion. The formation of partial oxidation products is enhanced by low temperatures as would occur in steam-assisted smokeless flaring or flame quenching. Excessive use of steam produces a white steam plume and an invisible emission of unburned hydrocarbons (Ref. 5).

In spite of the air pollution associated with emission of unburned hydrocarbons and partial oxidation products, there is little evidence of flare design modifications to suppress emissions resulting from incomplete combustion. Little actual experimental data of flare emissions are available, mostly for reasons of sampling difficulty. DuPont (unpublished report) has recently begun a development program for measuring flare emissions by using helium as a tracer to account for sample dilution.

Low-level enclosed flares should produce fewer unburned hydrocarbons and partial oxidation products because of their lower design velocities.

4.3.5 Oxidation Products

Emissions in the form of complete combustion products may occur in some cases, such as when flaring NH_3 , H_2S , or organic bases containing heteroatoms such as sulfur and nitrogen. API Manual on the Disposal of Refinery Wastes (Ref. 4) recommends other methods for disposal of these gases or vapors. Flaring is recommended only as a last resort, when other methods of disposal are not available. Alternate methods typically involve collection of the streams by vacuum or pressure methods, or solution (scrubbing), usually followed by a treatment of gases for segregation of contaminating constituents. Incineration in thermal or catalytic afterburners (Ref. 15) may also be a practical alternative if waste streams containing contaminants can be isolated and when the waste steam load is fairly constant.

It is frequently found that flares are used for the disposal of such gases, however. Hydrogen sulfide streams in particular are frequently included in flared waste streams. In these cases, the type of gas affects chiefly the height of the flare stack and materials of construction. Stainless steel types 304, 309 and 310 have been found to be particularly sensitive to failure due to intergranular corrosion promoted by sulfur acids. Inconel 800 or 629 are recommended for use in flare tips, stainless steel types 321 or 347, Inconel 625 or Incoloy 800 or 801 are recommended for use in steam rings when streams containing sulfur compounds are being flared (Ref. 33).

Flare heights are chosen to provide adequate dispersion of either flared streams (in the event of flame extinguishment) or combustion products according to methods that will be discussed. Local regulations are used to establish maximum ground level concentrations; in some cases these regulations may also dictate which dispersion model must be used and which gases may not be included in flared streams. In the combustion of organic bases, some estimate of conversion efficiency to toxic or harmful compounds must be obtained for the sizing calculation. For example, in the combustion of nitrogen-containing fuels, NO_2 may be further decomposed to N_2 and NO by secondary reaction. In the oxidation of fuel nitrogen in a diffusion flame, conversion to NO and NO_2 varies with nitrogen content, combustion efficiency, flame temperature, and residence time in the flame, but typically ranges from 20 to 100% of theoretical (Ref. 15). A detailed calculation is available for nitrogen-containing fuels (Ref. 34). Such information is not available for oxidation of waste streams containing chlorine, sulfur, phosphorous or other heteroatoms. In the absence of detailed information, it is recommended that the equilibrium product distribution be used for the sizing calculation.

4.3.6 Other Gaseous Emission Sources

Other sources of air pollution from industrial flaring include emission of unflared hydrocarbons from vent lines and formation of nitrogen oxides in the combustion process resulting from the contact of nitrogen in the air with oxygen at the elevated flame temperature. To reduce flare system cost, it has been a practice to vent gases of less than 40 mole weight directly to the atmosphere with the remainder being sent to the flare (Ref. 23), and this may contribute to the air pollution problem. Because of the use of steam in most flare systems, flame temperatures will be lower and emission factors for NO_x will be lower than, for example, gas-fired burners. Experimental measurement of NO_x emissions from elevated flares is difficult, but such measurements from low level flares is practical and should serve as an upper limit for elevated flares with steam injection. Experimental studies by a major flare vendor including NO_x measurements of a low-level flare unit are being conducted at this time.

4.3.7 Dispersion of Chemical Emissions and Flammable Gases

Chemical emissions from the flare may result from flame extinguishment while flaring toxic gases, as either complete or partial combustion products or as unburned fuel. In many cases the exact type and volume of chemical pollutants is difficult to predict. However, when flaring streams containing ammonia or trace amounts of phosgene, hydrogen sulfide, and hydrogen cyanide, height is frequently determined by possible atmospheric emissions rather than thermal considerations (Ref. 35). Even when hydrocarbons are being flared, high concentrations emitted during flame extinguishment may cause asphyxiation or exceed the lower flammability limit for the fuel at or near ground level. Since, apart from state, local, and federal requirements, emissions may represent a safety hazard to plant operations through loss of efficiency of operating personnel or low-level fire and explosion hazards, sizing of flare stacks should include design calculations to ensure that dispersion is sufficient to prevent concentrations of flammable or physiologically harmful emissions from exceeding safe limits at ground level.

Two distinct cases arise. For the case in which small concentrations of pollutants are emitted from the flare in the parts-per-million range, rapid mixing of the pollutants with the air occurs, and net changes in bulk density do not result in appreciable fallout rates. In this case, the pollutants remain suspended in the ambient air and diffuse at the same rate as the air. The concentration build-up at ground level occurs at a predictable rate. This build-up can be determined by applying classical atmospheric dispersion equations.

Unignited discharges which are heavier than air may occur in the event of flame extinguishment. Although these discharges do not have appreciable particle settling rates, fallout may occur because of the higher density of the bulk layer than the surrounding air. Very little published information is available to describe the safety hazards which may accompany this phenomenon. A recent study at DuPont on safety hazards of

unflared discharges recommends the following design equation based on wind tunnel studies (Ref. 36):

$$h_s = 1.33 (E) (D)^2 \quad (4.8)$$

where

- h_s = vent height above exposure level, ft
- E = number of dilutions of stack gas with air to reach lower explosive limit
- D = diameter of vent tip, ft.

The design equation is recommended only for short-period emergency releases of heavier-than-air gases. One additional factor which is known to be significant is the stack gas velocity.

For the case of small concentrations of contaminants or discharges which have molecular weights less than or approximately the same as the ambient air, dispersion from flare stacks and other elevated sources is modeled using Gaussian probability function to account for spreading and dilution of pollutants by diffusion. According to the Gaussian model, the emitted plume from a continuous source diffuses in the two directions perpendicular to the wind (Fig. 4-1). The maximum ground level concentration occurs at the distance from emission where the vertical downward diffusion equals the emissions height and the spreading plume touches the ground. On level terrain, this condition is expressed by the equation (Ref. 37):

$$\sigma_z(x) = H\sqrt{2} \quad (4.9)$$

where

- H = the effective height of emission
- $\sigma_z(x)$ = the vertical diffusion coefficient (corresponds to distance).

The vertical and horizontal diffusion coefficients are standard deviations for the Gaussian model. These are related to the eddy diffusivity. Dispersion of emissions in air occurs more rapidly than would be predicted from molecular diffusion and all gases and suspended particles diffuse at approximately the same rate (Ref. 38). Mixing is dominated by atmospheric turbulence which is supported by temperature and velocity gradients. Therefore, the vertical and horizontal diffusion coefficients depend on atmospheric conditions and are usually determined from empirical correlation.

Atmospheric conditions may also lead to conditions in which the continuous dispersion model is no longer valid. In the presence of a low level inversion layer, "trapping" of the emitted plume by the inversion layer may result in an increase in ground level concentrations (Refs. 39 and 40). Ground level

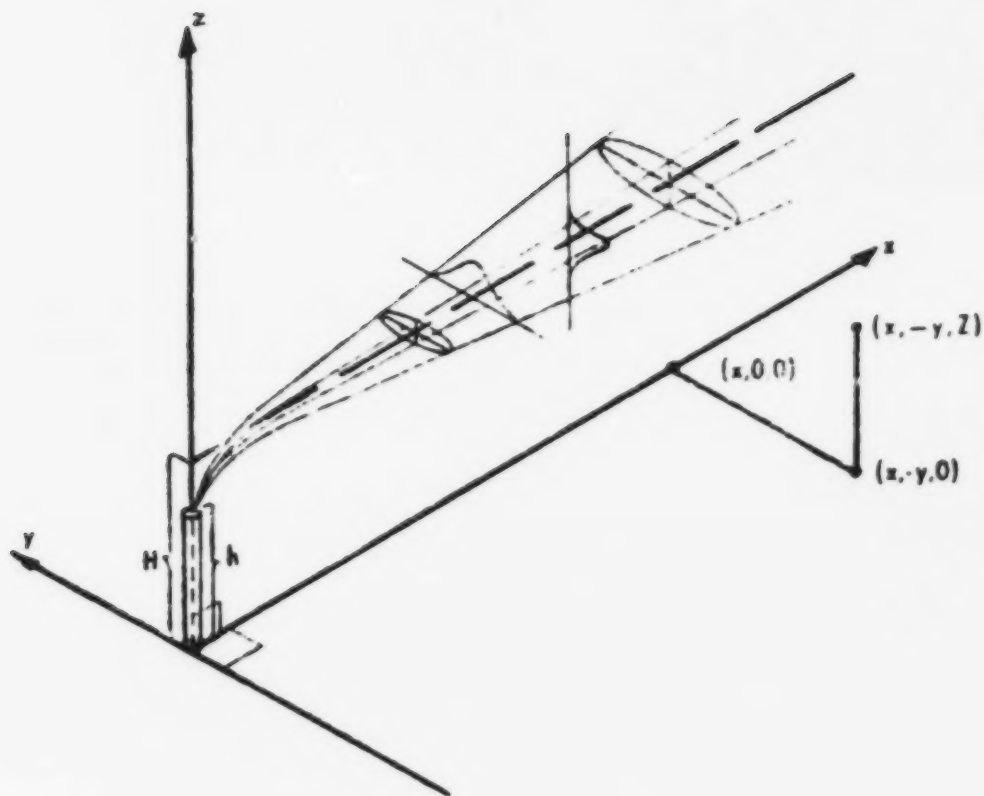


Fig. 4-1 - Coordinate System Showing Gaussian Distributions
in the Horizontal and Vertical (from Turner, Ref. 39)

concentrations may also increase beyond the level calculated for normal conditions during inversion breakup or "fumigation." In certain geographical areas, frequent occurrence of these phenomena may prevent the safe emission of certain chemicals at any height.

Chemical emissions may be classified as (Ref. 4):

1. Toxic gases and vapors
2. Irritants
3. Malodorous gases and vapors
4. Asphyxiants
5. Aerosols - smoke, mists and fumes
6. Dust and ash.

Threshold limits for a number of toxic substances set by the American Conference of Governmental Industrial Hygienists are given in Table 4-1. Limits of detection of selected odorous and noxious gases are given in Table 4-2 (API Manual). The lower flammability limits for gases and vapors being flared can be obtained from general references such as Bureau of Mines Bulletin No. 503 (Ref. 41). More recent references which provide flammability limits and toxicity data include the handbook Industrial Hygiene and Toxicology (Ref. 42), the Factory Mutual Engineering Corporation publication, Handbook of Industrial Loss Prevention (Ref. 43) and the Bulletin of the Bureau of Mines, "Flammability Characteristics of Gases and Vapors" (Ref. 44).

Dispersion models derived assuming a continuous plume are based on the original publication by Sutton (Ref. 45). More recent "coning" models for continuous dispersion differ chiefly in the method used for estimation of the dispersion coefficients. API RP 521 (Ref. 12) recommends the use of a weighted Gaussian distribution function for the calculation of required stack height. Given the maximum allowable concentration (max) at ground level, the required stack height may be calculated from the following:

$$C_{\max} = 3,697 \frac{VM}{u h^2} \frac{D_z}{D_y} \quad (4.10)$$

where

- $C_{\max}$ = parts per million of polluting gas (maximum ground level concentration)
- M = tons of polluting gas emitted per day
- V = volume of polluting gas, ft³/lb
- D_y, D_z = horizontal and vertical dispersion coefficients, ft
- u = air velocity, mph
- h = height of stack, ft.

Table 4-1

THRESHOLD LIMITS** FOR CERTAIN TOXIC SUBSTANCES

Gases and Vapors					
Gas or Vapor	PPM*	Gas or Vapor	PPM*	Gas or Vapor	PPM*
Acetaldehyde	200	Dimethylaniline (N-dimethylaniline)	5	Methylcyclohexanone	100
Acetic acid	10	Dimethylsulfate	1	Methyl formate	100
Acetic anhydride	5	Dioxane (diethylene dioxide)	100	Methyl isobutyl carbinol (methyl amyl alcohol)	25
Acetone	1,000	Ethyl acetate	400	Methylene chloride (dichloromethane)	500
Acrolein	0.5	Ethyl alcohol (ethanol)	1,000	Naphtha (coal tar)	200
Acrylonitrile	20	Ethylamine	25	Naphtha (petroleum)	500
Allyl alcohol	5	Ethylbenzene	200	Nickel carbonyl	0.001
Allyl propyl disulfide	2	Ethyl bromide	200	p-Nitroaniline	1
Ammonia	100	Ethyl chloride	1,000	Nitrobenzene	1
Amyl acetate	200	Ethyl ether	400	Nitroethane	100
Amyl alcohol (isoamyl alcohol)	100	Ethyl formate	100	Nitrogen dioxide	5
Aniline	5	Ethyl silicate	100	Nitroglycerin	0.5
Arsine	0.05	Ethylene chlorohydrin	5	Nitromethane	100
Benzene (benzol)	35	Ethylenediamine	10	2-Nitropropane	50
Benzyl chloride	1	Ethylene dibromide (1,2-dibromoethane)	25	Nitrotoluene	5
Bromine	1	Ethylene dichloride (1,2-dichloroethane)	100	Octane	500
Butadiene (1,3-butadiene)	1,000	Ethylene imine	5	Ozone	0.1
Butanone (methyl ethyl ketone)	250	Ethylene oxide	100	Pentane	1,000
Butyl acetate (n-butyl acetate)	200	Fluorine	0.1	Pentanone (methyl propyl ketone)	200
Butyl alcohol (n-butanol)	100	Fluorotrichloromethane	1,000	Perchloroethylene (tetrachloroethylene)	200
Butylamine	5	Formaldehyde	5	Phenol	5
Butyl cellosolve (2-butoxyethanol)	200	Gasoline	500	Phenylhydrazine	5
Carbon dioxide	5,000	Heptane (nheptane)	500	Phosgene (carbonyl chloride)	1
Carbon disulfide	20	Hexane (nhexane)	500	Phosphine	0.05
Carbon monoxide	100	Hexanone (methyl butyl ketone)	100	Phosphorus trichloride	0.5
Carbon tetrachloride	25	Heptanone (methyl isobutyl ketone)	100	Propyl acetate	200
Cellosolve (2-ethoxyethanol)	200	Hydrazine	1	Propyl alcohol (isopropyl alcohol)	400
Cellosolve acetate (2-ethoxyethyl acetate)	100	Hydrogen bromide	5	Propyl ether (isopropyl ether)	500
Chlorine	1	Hydrogen chloride	5	Propylene dichloride (1,2-dichloropropane)	75
Chlorine trifluoride	0.1	Hydrogen cyanide	10	Propylene imine	25
Chlorobenzene (monochlorobenzene)	75	Hydrogen fluoride	3	Pyridine	10
Chloroform (trichloromethane)	100	Hydrogen peroxide, 90 per cent	1	Quinone	0.1
1-Chloro-1-nitropropane	20	Hydrogen selenide	0.05	Stibine	0.1
Chloroprene (2-chloro-1,3-butadiene)	25	Hydrogen sulfide	20	Stoddard solvent	500
Cresol (all isomers)	5	Iodine	0.1	Styrene monomer (phenylethylene)	200
Cyclohexane	400	Isophorone	25	Sulfur dioxide	10
Cyclohexanol	100	Isopropylamine	5	Sulfur hexafluoride	1,000
Cyclohexanone	100	Mesityl oxide	50	Sulfur monochloride	1
Cyclohexene	400	Methyl acetate	200	Sulfur pentafluoride	0.025
Cyclopropane	400	Methyl acetylene	1,000	p-Tertiarybutyltoluene	10
Diacetone alcohol (4-hydroxy-4-methyl-2-pentanone)	50	Methyl alcohol (methanol)	200	1,1,2,2-Tetrachloroethane	5
Diborane	0.1	Methyl bromide	20	Tetranitromethane	1
o-Dichlorobenzene	50	Methyl cellosolve (2-methoxyethanol)	25	Toluene (toluol)	200
Dichlorodifluoromethane	1,000	Methyl cellosolve acetate (ethylene glycol monomethyl ether acetate)	25	o-Toluidine	5
1,1-Dichloroethane	100	Methyl chloride	100	Trichloroethylene	200
1,2-Dichloroethylene	200	Methylal (dimethoxymethane)	1,000	Trifluoromonobromomethane	1,000
Dichloroethyl ether	15	Methyl chloroform (1,1,1-trichloroethane)	500	Turpentine	100
Dichloromonofluoromethane	1,000	Methylcyclohexane	500	Vinyl chloride (chloroethylene)	500
1,1-Dichloro-1-nitroethane	10	Methylcyclohexanol	100	Xylene (xytol)	200
Dichlorotetrafluoroethane	1,000				
Diethylamine	25				
Difluorodibromomethane	100				
Diisobutyl ketone	50				

Table 4-1 (Continued)

Toxic Dusts, Fumes, and Mists			
Dust, Fume, or Mist	Mg per Cu M†	Dust, Fume, or Mist	Mg per Cu M†
Aldrin (1,2,3,4,10,10-hexachloro-1,4,4a,5,8,8a-hexahydro-1,4,5,8-dimethanonaphthalene).	0.25	Magnesium oxide fume	15
Ammate (ammonium sulfamate)	15	Malathion (O,O-dimethyl dithiophosphate of diethyl mercaptosuccinate)	15
Antimony	0.5	Manganese	6
Arsenic	0.5	Mercury	0.1
Barium (soluble compounds)	0.5	Mercury (organic compounds)	0.01
Cadmium oxide fume	0.1	Methoxychlor (2,2-di-p-methoxyphenyl-1,1,1-trichloroethane)	15
Chlordane (1,2,4,5,6,7,8,8-octachloro-3a,4,7,7a-tetrahydro-4,7-methanoidane)	2	Molybdenum (soluble compounds)	5
Chlorinated diphenyl oxide	0.5	Molybdenum (insoluble compounds)	15
Chlorodiphenyl (42 per cent chlorine)	1	Parathion (O,O-diethyl O-p-nitrophenyl thiophosphate)	0.1
Chromic acid and chromates (as CrO ₃)	0.1	Pentachloronaphthalene	0.5
Crag herbicide (sodium 2-[2,4-dichlorophenoxy] ethanol hydrogen sulfate)	15	Pentachlorophenol	0.5
Cyanide (as CN)	5	Phosphorus (yellow)	0.1
2,4-D (2,4-dichlorophenoxyacetic acid)	10	Phosphorus pentachloride	1
Dieldrin (1,2,3,4,10,10-hexachloro-6,7-epoxy-1,4,4a,5,6,7,8,8a-octahydro-1,4,5,8-dimethanonaphthalene)	0.25	Phosphorus pentasulfide	1
Dinitrotoluene	1.5	Picric acid	0.1
Dinitro-o-cresol	0.2	Selenium compounds (as Se)	0.1
EPN (O-ethyl O-p-nitrophenyl thionobenzenephosphonate)	0.5	Sodium hydroxide	2
Ferrovandium dust	1	Sulfuric acid	1
Fluoride	2.5	TEDP (tetraethyl dithionopyrophosphate)	0.2
1,4-dioquinone	2	TEPP (tetraethyl pyrophosphate)	0.05
Iron oxide fume	15	Tellurium	0.1
Lead	0.15	Tetryl (2,4,6-trinitrophenylmethyl nitramine)	1.5
Lindane (hexachlorocyclohexane, gamma isomer)	0.5	Titanium dioxide	15
		Trichloronaphthalene	5
		Trinitrotoluene	1.5
		Uranium (soluble compounds)	0.05
		Uranium (insoluble compounds)	0.25
		Vanadium (V ₂ O ₅ dust)	0.5
		Vanadium (V ₂ O ₅ fume)	0.1
		Zinc oxide fumes	15
		Zirconium compounds (as Zr)	5

Radioactivity: For permissible concentrations of radioisotopes in air, see "Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water," Handbook 52, U.S. Department of Commerce, National Bureau of Standards, March 1953. See also, "Permissible Dose from External Sources of Ionizing Radiation," Handbook 59, U.S. Department of Commerce, National Bureau of Standards, Sept. 24, 1954.

Mineral Dust	MPPCF‡
Aluminum oxide	50
Asbestos	5
Dust (nuisance, no free silica)	50
Mica (below 5 per cent free silica)	20
Portland cement	50
Talc	20
Silica	
High (above 50 per cent free SiO ₂)	5
Medium (5 to 50 per cent free SiO ₂)	20
Low (below 5 per cent free SiO ₂)	50
Silicon carbide	50
Slate (below 5 per cent free SiO ₂)	50
Soapstone (below 5 per cent free SiO ₂)	20
Total dust (below 5 per cent free SiO ₂)	50

* Parts of gas or vapor per million parts of air by volume.

† Milligrams of dust, fume, or mist per cubic meter of air.

‡ Millions of particles per cubic foot of air.

Source: "Threshold Limit Values for 1956," 18th Annual Meeting, American Conference of Governmental Industrial Hygienists, Philadelphia, Apr. (1956).

Threshold limit values define the concentration levels of chemical compounds and physical agents below which the average healthy worker will suffer no demonstrably damaging effects.

Table 4-2

Possible Contaminating Compound	Chemical Formula	Molecular Weight	Density (Air = 1)	Boiling Point (Fahrenheit)	Lowest Detectable Concentration, Parts per Million	Dilution in Air at 35° and 100° (Cu. per Sec.)	First Physiologic Effect from Prolonged Exposure to High Concentrations
Acetaldehyde	CH ₃ CHO	44.05	2.14	68	0.71	0.100†	Irritant
Acetic Acid	CH ₃ COOH	58.95	2.00	133	4.10	0.083†	Irritant, anesthetic
Acetic Anhydride	(CH ₃ CO) ₂ O	60.03	2.07	243	7.00	0.106†	Irritant
Hydrogen chloride	HCl	36.47	3.16	-121	9.40†	2.40†	Nauseating
Hydrogen fluoride	HF	20.01	0.69	87	...	0.128†	Irritant
Alcohol	C ₂ H ₅ OH	32.03	1.11	148	580.00	...	0.149
Ethyl Ether	C ₂ H ₅ OCH ₂ CH ₃	45.04	1.55	173	410.00	...	Anesthetic, blinding
Propyl Ether	C ₃ H ₇ OCH ₂ CH ₂ CH ₃	60.06	2.07	207	3.10	0.094†	Slightly irritant, anesthetic
Isopropyl Ether	(CH ₃) ₂ CHOCH ₂ CH ₃	60.06	2.07	180	...	0.085†	Anesthetic
Isobutyl Ether	(CH ₃) ₂ CHCH ₂ OCH ₂ CH ₃	74.08	2.56	244	...	0.082†	Slightly irritant
Ampl.	C ₄ H ₉ OH	74.08	2.56	260	0.0035	0.073†	Slightly irritant
Isopentyl	C ₅ H ₁₁ OH	88.10	3.04	280	0.0030	0.063	Slightly irritant
Ammonia	NH ₃	17.03	0.59	-28	240.60†	63.00†	Irritant
Chlorine	Cl ₂	70.91	3.44	-34	0.0010	0.0026	Irritant
Ethyl ether	C ₂ H ₅ OCH ₂ CH ₃	74.08	2.56	173	4.00	0.170†	Irritant
Hydrocarbons					11.00	0.093†	Anesthetic
Paraffins					0.76	0.078†	Anesthetic
Methane	CH ₄	16.04	0.555	-258.7	Not detectable	...	Anesthetic
Ethane	C ₂ H ₆	30.07	1.046	-127.5	Not detectable	...	Anesthetic
Propane	C ₃ H ₈	44.09	1.547	-43.7	Not detectable	...	Anesthetic
Isobutane	C ₄ H ₁₀	58.12	2.071	31.1	Not detectable	...	Anesthetic
Isopentane	C ₅ H ₁₂	72.15	2.067	10.9	Not detectable	...	Anesthetic
Isopentane	C ₅ H ₁₂	72.15	2.066	90.9	Not detectable	...	Anesthetic
Isopentane	C ₅ H ₁₂	72.15	2.066	82.1	Not detectable	...	Anesthetic
Olefins							
Ethylene	C ₂ H ₄	28.05	0.9684	-164.7	Not detectable	...	Anesthetic
Propylene	C ₃ H ₆	42.08	1.4526	-53.9	Not detectable	...	Anesthetic
Isobutylene	C ₄ H ₈	56.10	1.9368	-20.7	Not detectable	...	Anesthetic
Isopentylene	C ₅ H ₁₀	70.12	1.9368	19.6	Not detectable	...	Anesthetic
Cyclopropane	C ₃ H ₆	42.08	1.4526	-33.0	Not detectable	...	Anesthetic
Acetylene	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H ₂	26.04	2.4211	120.7	Not detectable	...	Anesthetic
Alkyne							
Ethyne	C ₂ H _{2</}						

1 International Critical Tables, 3 271.3, McGraw-Hill Book Co. Inc., New York 10331.
2 U.S. Bur. Mines Tech. Paper 867.

The calculation is reported to be valid, on the conservative side, within a factor of 2 within about six miles and to within a factor of 5 for greater distances.

The eddy diffusion factors D_z and D_y are dependent upon atmospheric stability and discharge height. For emissions at heights greater than about 25 feet and for "neutral" atmospheric conditions (lapse rate equal to the dry adiabatic rate)* the ratio D_z/D_y is approximately unity. For a given stack height, the maximum ground level concentration may vary by as much as a factor of two under varying atmospheric conditions. The calculation is based on the original report published in 1932 (Ref. 45). An expression reported by Bosanquet and Pearson (1936) is of a similar form. As applied to the calculation of the required stack height (Ref. 46):

$$C_{\max}(x, y) = 1.55 \times 10^4 \frac{W_c}{uH^2 M_c} \frac{p}{q} \quad (4.11)$$

where

- W_c = emission rate of contaminant, lb/hr
- $C_{\max}$ = maximum concentration of contaminants contained in the air-gas stream at ground level downwind from the stack of a point where $x = H/2p$ and $y = 0$
- M_c = molecular weight of the contaminant
- p = vertical diffusion coefficient, dimensionless
- q = horizontal diffusion coefficient, dimensionless
- u = mean wind speed, mph
- x = horizontal distance downwind from point of emission, ft
- y = horizontal distance crosswind from point of emission, ft
- H = effective stack height above ground, ft (physical stack height plus plume height caused by the velocity of the stack gases plus rise of plume caused by difference in density between stack gases and the surrounding atmospheres)

Bosanquet-Pearson Turbulence Parameters (Ref. 46)

	p	q	p/q
Low turbulence	0.02	0.04	0.50
Average turbulence	0.05	0.08	0.63
Moderate turbulence	0.10	0.16	0.63

* Lapse rate is defined as the rate of decrease of atmospheric temperature with increase in height, while the dry adiabatic rate is $5.50^\circ\text{F}/1000\text{ ft}$

A number of empirical expressions are available for estimating plume height above the stack (Refs. 47 and 48). The plume rise is sometimes included in the design safety factor since the case $\Delta h = 0$ corresponds to the upper ground level concentration limit.

Both the dispersion models of Sutton (1932) and Bosanquet-Pearson (1936) are based on experimental data and are widely used for flare stack sizing (Ref. 35). Sample "averaging times" differ between the two methods; this is reflected in the difference between Sutton's σ coefficients and the Bosanquet-Pearson turbulence parameters, p and q . Sutton's method as applied to stack sizing (Ref. 4) is based on a three-minute interval and is usually considered conservative. In practice, chemical companies have tended to use the Bosanquet-Pearson equation which is based on a 30-minute concentration interval (Ref. 49). Sample averaging time affects the design stack height since, because of wind fluctuations, instantaneous concentrations are much higher than concentrations averaged over time periods long enough to be physiologically significant. The effect of sample averaging time on concentration is discussed by Turner (Ref. 39). Comparison of stack heights calculated on the basis of Sutton's and Bosanquet-Pearson methods is given in Ref. 2.

The dispersion model chosen and required averaging times will frequently depend not only upon plant safety but also upon local air quality regulations. Turner's Workbook of Atmospheric Dispersion Estimates (Ref. 39) is recommended for use by the U.S. Environmental Protection Agency and is considered typical of recent guidelines. The chief advantage of the more recent techniques appears to be in the measuring techniques used in estimating the diffusion coefficients and the inclusion of methods applicable to more severe atmospheric conditions.

Atmospheric or "eddy" diffusion coefficients, σ , given by Turner (Ref. 39) are given as functions of downwind distance and atmospheric conditions. The most severe conditions correspond to stagnant wind conditions and strong sunlight. Under these conditions, the maximum ratio of σ_z/σ_y is about 2.0 within about 1000 meters. The instantaneous maximum concentration at ground level is:

$$X_{\max}(x, H) = \frac{2Q}{e\pi uH^2} \frac{\sigma_z}{\sigma_y} \quad (4.12)$$

where

H = effective discharge height, m

X = concentration of gases or aerosols, g/m^3
(particles $< 20\mu$)

Q = emissions rate, g/sec

u = mean wind velocity, m/sec

σ_z, σ_y = horizontal and vertical dispersion coefficients.

$\pi = 3.14$

$e = 2.72$

Conditions which may significantly affect the maximum ground level concentration include fumigation and plume trapping in the presence of a low level inversion layer. In some cases, terrain effects must also be considered (Ref. 39).

Fumigation or inversion breakup may occur when a superadiabatic rate develops in the lowest layer in the atmosphere. This situation occurs when the surface is warmer than the overlying air such as in conditions when the ground is being warmed by solar radiation or when air flows from a cold to a relatively warm surface (Refs. 4 and 39). Impingement of the resulting vertical air current with the plume may break up the plume and bring isolated portions of it to the ground almost undiluted (Ref. 4). The heavy concentration of polluting materials may persist for as long as 30 minutes (Refs. 2 and 40). The equations for estimating maximum ground level concentrations during fumigation conditions is based on an adaptation of Eq. (4.10).

$$\chi_F = \frac{Q}{\sqrt{2\pi} u \sigma_{yf} h_1} \quad (4.13)$$

where

$$h_1 = H + 2\sigma_z$$

$$\sigma_{yf} = \sigma_y + H/8$$

χ , Q , u as previously defined

The presence of a trapping inversion layer at mixing height, L , leads to higher ground level concentrations, depending on the height above ground of the inversion layer (Ref. 39):

$$\chi = \frac{Q}{\sqrt{2\pi} \sigma_y L u} \exp\left[-\frac{1}{2} (y/\sigma_y)^2\right] \quad (4.14)$$

It has been observed that the surface concentration may be increased by as much as a factor of 3 for mixing heights ranging from 760 to 1065 meters (Ref. 40). The mixing height limitation will not be significant if the concentration maximum calculated from Eq. (4.9) occurs within a relatively short distance from the stack. This distance x_L (corresponding to σ_z) is given by the approximate equation (Ref. 39):

$$\sigma_z = 0.47L \quad (4.15)$$

For distances $x \geq x_L$, the invariance of Eq. (4.14) with stack height may limit the total rate of certain chemical emissions.

4.3.8 Air Pollution Rules and Regulations Affecting Flares

The 1970 Clean Air Amendments (Ref. 50) have provided three rule-setting mechanisms that could directly affect the flaring of waste streams in the United States: (1) national primary and secondary ambient air quality standards, (2) standards of performance for new stationary sources, and (3) national emission standards for hazardous air pollutants.

National Primary Air Quality Standards are time-based, maximum-allowable ambient air pollutant concentrations that can be tolerated without adversely affecting public health. Secondary standards are those concentrations of a pollutant that can be tolerated on a time basis without affecting public welfare. Setting and enforcing emission control regulations to ensure that ambient air standards are met is a state function. Both primary and secondary standards have been published for six classifications of pollutants - sulfur oxides, particulate matter, carbon monoxide, photochemical oxidants, hydrocarbons and nitrogen dioxide (Ref. 51) and are summarized in Table 4-3. Ambient air standards are most applicable when applied against pollutants that are emitted by a large number of different sources. Except in special cases, such as flaring a high H_2S stream, it is unlikely that flaring alone will cause ambient air quality standards to be exceeded. Many states restrict the flaring of H_2S , chlorinated hydrocarbons or other gases whose combustion products they feel may cause an emissions problem.

Table 4-3

NATIONAL PRIMARY AND SECONDARY STANDARDS

Pollutant	Time Basis	Primary Standard ($\mu g/m^3$)	Secondary Standard ($\mu g/m^3$)
Sulfur oxides (measured as SO_2)	Annual arithmetic mean.	80	60
	Maximum 24-hr concentration (not to be exceeded more than once/yr).	365	260 ^a
	Maximum 3-hr concentration (not to be exceeded more than once/yr).	-	1300
Particulate matter	Annual geometric mean.	75	60
	Maximum 24-hr concentration (not to be exceeded more than once/yr).	260	150
Carbon monoxide	Maximum 8-hr concentration (not to be exceeded more than once/yr).	10,000	10,000
	Maximum 1-hr concentration (not to be exceeded more than once/yr).	40,000	40,000
Photochemical oxidants (measured as ozone)	Maximum 1-hr concentration (not to be exceeded more than once/yr).	160	160
Hydrocarbons, except methane (measured as methane)	Maximum 3-hr concentration, 6-9 a.m. (not to be exceeded more than once/yr).	160	160
Nitrogen dioxide	Annual arithmetic mean.	100	100

^a A proposal to drop this standard is being considered (see Ref. 52).

New stationary source performance standards are allowable emissions for new or modified emission sources. The mechanism regulates a specific industry rather than a pollutant. The Federal Government has primary responsibility for enforcing new source standards. It can be delegated however, to qualified State control agencies. When Federal new source performance standards are set, the law requires that State governments establish emission standards for the same existing sources. Although the rule making is a state function, the variation of the standards across the nation may be relatively small (Ref. 56).

The performance standard for new petroleum refineries is the only one that specifically mentions flares (Ref. 53). Standards limit only the emission of sulfur dioxide from flares. These standards limit the emission of sulfur dioxide from fuel gas combustion systems which include flares. The regulation prohibits the burning of any fuel gas which contains H_2S in excess of 230 mg/dry scm unless the resulting gases are treated to reduce the release of SO_2 to the atmosphere. However, the combustion of process upset gas in a flare, or the combustion in a flare of process gas or fuel gas which is released to the flare as a result of relief valve leakage, is exempt from the regulation. Process upset gas means any gas generated by a petroleum refinery process unit as a result of start-up, shut-down, upset or malfunction.

Smoke emissions are limited from new sources by opacity standards. The standard limits the time, two minutes per hour, when the average opacity can exceed 20%. All hourly periods during which there are three or more one-minute periods when the average opacity exceeds 20% are considered periods of excess emission and must be reported. However, the opacity standards do not apply during periods of start-up, shut-down and malfunction. The opacity standards in effect require flares to operate smokeless except for emergency occurrences. All states have opacity standards for existing sources which require smokeless flaring at least for the major portion of the time.

National emission standards for hazardous air pollutants provide the third standard setting tool. A hazardous air pollutant is defined as one that "will cause or contribute to an increase in mortality or an increase in serious irreversible or incapacitating reversible illness (Ref. 54)." Asbestos, beryllium and mercury have been designated hazardous pollutants and allowable emission standards have been set (Ref. 55). The extent to which this rule-setting tool will be used to set standards for other hazardous pollutants is unclear at present (Ref. 56).

The Province of Alberta, Canada, has a number of sour gas processing plants (gas containing hydrogen sulfide). Normal releases of tail gas from these plants must be incinerated. All plant emergency releases of sour gas are required to be flared in specially designed flare stacks with an adequate amount of fuel gas so as to ensure gases with low heating values are successfully flared (Ref. 57). Their experience has shown that a minimum of 250 Btu/ft³ of gas going to the flare should be

maintained. The additional fuel gas serves two purposes. It ensures a more complete combustion of the gas and also gives the combustion products a greater lift off the stack. Depending on the length of the flaring and the amount of gas to be flared, the height of the flare stack is designed so that the resulting ground level SO_2 concentration does not exceed 0.2 ppm for flaring greater than one hour and 1 ppm for flaring less than one hour. The computational method used for the expected ground level pollutant concentration and thus the estimation of stack height required are the Sutton equation with the Lowry modification for the case of even ground and the Pasquill method for the case of uneven ground.

In populated areas the flare's flame has caused a nuisance to people living nearby. In parts of Germany regulations limit the amount of time that an elevated flare can be used (Ref. 27). Ground level enclosed flares must be used to hide the flame for 95% of the time the flare operates. The elevated flare is used only for severe emergencies.

The main thrust of the air pollution regulations on flares has been toward smokeless operation, at least for most flare occurrences. Many states further prohibit or restrict flaring of waste streams whose combustion products may cause an emissions problem. However, restrictions do not apply during upset conditions when safety is the overriding concern. Very little is known about the emissions of unburned hydrocarbons, carbon monoxide and nitrogen oxides from flares and as long as ambient standards are met there are no regulations or standards affecting these emissions.

4.3.9 Flare Emission Factors

The emission factor is a statistical average or a quantitative estimate of the rate at which a pollutant is released to the atmosphere as a result of an activity such as combustion or industrial production, divided by the level of that activity. The emission factor thus relates the quantity of pollutants emitted to some indicator of activity such as production capacity, quantity of fuel burned, or vehicle miles traveled. Emission factors may be found in a number of literature sources. The most complete collection of factors has been published by the Environmental Protection Agency in AP-42, Compilation of Air Pollutant Emission Factors (revised 1973) (Ref. 58). Emission factor accuracy and reliability are dependent upon many variables. It is generally accepted that emission factors generated from on-site source-test data are preferred and will give more realistic estimates than those developed strictly from engineering analysis or material balances (Ref. 59).

The EPA compilation lists, in the section for petroleum refining, an emission factor for the "vapor recovery system or flaring." The hydrocarbon emission factor is given as 5 pounds per 1000 barrels of refining capacity. Emissions of particulates, sulfur oxides, carbon monoxide, aldehydes, ammonia and nitrogen oxides are listed as negligible. The basis for this factor on hydrocarbon emissions is not given, but it is unlikely that it is based on any on-site source-testing of flares.

Cross et al., (Refs. 60, 61) estimated refinery emission sources from hypothetical 100,000 barrel-per-day capacity refinery. The only significant emission that they considered coming from flares was NO. Their estimates of the NO emission factor for flares was 0.7 pounds per 1000 barrels of refinery capacity. They did not, however, give the basis for their estimate. Section VII discusses the results of a user's survey that was used to develop quantity and quality data on gases now being flared.

4.4 Flare Safety

Since the various flare systems were developed as a means of safely disposing of refinery and petrochemical wastes, the bulk of the design calculations involved in sizing the flare system are concerned with plant and operator safety. Flare tip diameter is sized for flame stability and maximum throughput within a given allowable pressure drop. However, knockout drum and design sizing, flare height, location and material of construction are based entirely on safety of operation. Primary considerations include explosion potential, toxicity and plume dispersion, and thermal radiation. The design bases for these calculations is described in detail in the following section.

4.4.1 Explosion Potential

Explosions associated with flaring result from two major sources - the formation of a flammable air-fuel mixture within the flare system which can be ignited by the pilot burner, and secondary explosions resulting from flare emissions of thermal radiation and burning liquid droplets. With the flare system operating normally during an upset, thermal radiation from the flame can produce sufficient heat to ignite flammable gases and liquids stored nearby. Usually resulting from malfunction of the knockout drum, injection of droplets of heavy liquids into the flare stack can produce a high velocity spray of burning liquid droplets which can cause damage to plant equipment and personnel.

Formation of air-fuel explosive mixtures within the flare system may result from:

1. Back-diffusion of air into the flare system,
2. Leaks in the flare system resulting from improper design or selection of valves and valve locations corrosion or low temperature failure of flare piping, and
3. Accidental injection of air during maintenance or in start-up following maintenance.

Formation of explosive mixtures within the flare system may result through design error in the mixing of reactive streams into a common flare system or through operator error in mixing reactive streams into a single flare system during flare maintenance.

4.4.2 Vapor Purging

Vapor purging has traditionally been used to prevent the formation of explosive mixtures in flare and vent systems by preventing the admission of air into the flare system through leaks, back-flow of air at the flare tip at very low flows and back-diffusion of air into the flare tip. Either combustible gases such as methane or natural gas, or inert gases such as nitrogen or CO, are frequently used as for purging flare systems (Ref. 62). Inert gas generators are commercially available which use the combustion products of natural gas (CO_2 , N_2) as the purge gas. Utilization of the combustion air in these generators allows purge gas (natural gas) to be reduced by about a factor of 11:1.

Back-diffusion of air becomes a problem at very low flare rates. In general, the diffusion or mixing process is more rapid and air influx rates greater when lighter gases are being flared (Refs. 12 and 62). When gases with molecular weights less than air are being flared (such as hydrogen or CO) the pressure at the flare tip may frequently be less than atmospheric, even with large gas flow rates (Ref. 12). A continuous flow of purge gas is generally required for such systems. Conversely, the effectiveness of the purge gas increases with molecular weight. Heavy gases tend to displace the air as a piston while lighter gases mix with the air and are less effective for displacement. An empirical equation for estimation of purge gas requirements has been given by Husa (Ref. 62). This correlation includes terms for diffusion and natural draft but ignores contributions from the molecular weight of the flared gas. Discussions with a flare vendor indicate that the correlation is not suitable for scale-up to flares having diameters larger than about 24 in.

In practice, vapor purging is frequently also used to maintain a stable flame at low flow rates to provide a flammable mixture or increase the heat content of flared gases. Purging therefore adds substantially to normal operating costs. Vapor purging is also required for displacement of air in vent systems prior to pilot ignition during normal start up, for example, following shut-down for maintenance.

Safety problems associated with vapor purging have been discussed in detail by Bluhm (Ref. 63). Internal explosions occur primarily by accidental introduction of air into the flare stack. Introduction of air occurs not only through back flow and diffusion but also results from improper selection of valves and other components, failure to purge the flare and associated lines following maintenance, and through malfunction of compressor controls on flares equipped with vapor recovery systems. Purging with flammable gases can also present safety problems if oxygen monitors are used to adjust flow rates since oxygen monitors do not differentiate between air entry from leaks and from back-flow and diffusion.

4.4.3 Molecular Seals

Molecular seals are intended to form a second line of defense against the entry of air into the flare stack. While in a vertical flare stack, gravity exerts an additional driving force to increase the diffusion of air into the stack, "molecular" seals create an inverted flow field to reverse the gravitational effect and further reduce air entry. Use of a lighter-than-air purge gas further creates a pocket of light gas at the top of the air entry path. Purge gases such as methane or natural gas are therefore most effective for flare systems equipped with a molecular seal. Use of a molecular seal and a lighter-than-air purge gas allows a much lower purge gas rate. Installation of the John Zink molecular seal (Ref. 64) at the top of the flare and immediately below the burning point (Fig. 3-8) reduces purge gas required to approximately 10% of the volume required if the molecular seal is not used (Ref. 65).

4.4.4 Fluidic Seal

A recent development in air reentry seal design uses baffles to redirect the flow field at a point near the flare tip and prevent air entry (Fig. 3-9). The fluidic seal (Ref. 66) reportedly requires only 25 to 33% of the purge gas used in molecular seals and weighs only 10% as much as the inverted seal. The fluidic seal is designed to be used instead of the molecular seal. Limited published information (Ref. 67) indicates that it has performed satisfactorily in its intended application.

4.4.5 Explosion Suppression Systems

Explosion suppression systems have recently been developed which are suitable for installation at the base of flare stacks (Ref. 68). The purpose of the system is to detect ignition using light or pressure sensors before the flame can propagate an appreciable distance. The sensing device fires an explosive activator discharging an extinguishing agent (typically a halogenated hydrocarbon) up and down the flow field through a tee. The elapsed time from the detection of an alarm condition to suppression may be only a few milliseconds. The first suppression system was installed at Sun Oil Company's Marcus Hook, Pennsylvania refinery in June 1967 (Ref. 8).

4.4.6 Water Seals and Flame Arrestors

Flame arrestors and water seals are intended to prevent a fire once started from spreading throughout the flare and vent system. Because of their weight these systems are typically located at or near the base of the flare stack and offer no protection for the stack itself. Either flame arrestor or water seals must be used if a flammable mixture is being flared.

Flame arrestors are typically long narrow passageways within a sponge-like metal structure designed to prevent flame propagation by chilling the burning gases below their ignition temperature. Flame arrestors have become somewhat unpopular for use in flare systems because of their tendency to plug, and are not recommended for use without an emergency by-pass arrangement (Ref. 63). A proprietary flame arrestor design is also available (John Zink Company) which combines the water seal with the barrier principle.

Water seals are normally provided in the gas inlet line to the flare at or near the base of the flare stack and are intended to prevent flash back to the flare header. These are of two types: pipe seals and seal drums. Pipe seals usually consist either of a loop in the flare inlet line or a trap built into the base of the flare stack. A pipe seal, therefore, provides only limited disengagement space for removal of water or condensed hydrocarbons. Seal drums are larger, usually more expensive, contain a larger liquid volume and provide both a liquid disengaging space and a reduction in liquid velocity above the liquid. Seal drums are thus less susceptible to pulsation at low flow rates, and have small likelihood of the water seal being blown at high vapor relief rates.

The seal drum is often incorporated into the base of the flare stack as part of the structural unit. When a separate drum is used, the drum should be located between the flare stack and the header drums and as close to the stack as possible (Ref. 12). Special design considerations include auto-refrigeration cooling of the gas inlet which requires auxiliary heating, solubility of the gas stream in the seal water, corrosiveness of the dissolved gas, and condensation of the gas stream in the liquid which requires continuous water inlet and skimming or removal of the liquid phase.

Under normal operating conditions, the most important design consideration is the stability of the liquid seal. This affects both the flashback protection and flame stability at low flow rates. Stability of the liquid seal is affected by the ratio of the inlet or outlet gas areas, dispersion of the gas into the seal liquid, the temperature of the gas inlet stream and maintenance of the liquid level by means of alarm and control devices.

Sizing requirements which are applicable to both drums and pipe seals are discussed in API RP 521 (Ref. 12). For seal drums, the recommended maximum ratio of inlet cross-section to vessel free area should be 1:3. The vapor space in a vertical seal drum should be 2 to 3 times the diameter to provide disengaging space for entrained seal liquid. A minimum disengaging space of three feet is suggested for a horizontal seal drum. For a pipe seal, the gas flow area above the seal should be at least as great as the inlet line area. This requirement is considerably less stringent than for drums, and pulsations are frequently encountered at low flows.

It is recommended (Ref. 12) that the seal contain a volume of water below the normal sealing line equivalent to the volume contained in a 10-foot length of the inlet line to prevent flashback. To reduce pulsations, the depth is arbitrarily limited to a maximum of about 12 inches.

Provisions for establishing and maintaining an adequate seal level are required. Because of the nature of the materials handled and the conditions under which components must operate, instrumentation for all parts of the flare and vent collection systems should be reliable, easy to maintain and readily available for replacement. For example, tri cocks (valves) may be desirable in addition to, or instead of, level gauges (Ref. 12).

Special design attention should be given to seals which are to be used for flaring heated gases or which may be subjected to thermal upsets. Cooling of the gas by the seal liquid will create a partial vacuum in the cooler disengagement portion of the seal drum. The construction of an inlet vacuum leg is recommended to compensate for this effect provided that the maximum inlet temperature and flow rate can be estimated. The additional volume of liquid in the inlet line required to form the vacuum leg must be contained within the seal drum and this may necessitate an increase in drum size (Ref. 12).

4.4.7 External Fires and Emissions

External fires may result from the discharge of burning liquids from the flare or from thermal emissions from luminous flames. Principal control methods include the use of knockout drums to separate flammable liquids and entrained liquid droplets, insulation and safety relieving of pressure vessels, remote location of the flare stack, and the injection of air, water, or steam into the flare tip to reduce luminosity. Knockout drums are usually located either between the process units and the collection system or at the flare itself. These require fairly precise level control of the accumulated liquids in order to prevent additional hazards from accumulated flammable liquids (Ref. 63). Design methods for insulation and relief value sizing of pressure vessels are discussed in the API Guide for Pressure Relief and Depressuring Systems (Ref. 12). Steam is widely used to reduce smoking and luminosity, but thermal emissions from flares have not been well quantified. For this reason, flare stacks are usually located several hundred feet from process units handling low-flash point materials (Ref. 69).

4.4.8 Knockout Drum Sizing and Design Criteria

The design method used for sizing knockout drums is based on experimental measurements of terminal velocities of spherical droplets in gases (Ref. 70). In the application of drum sizing, the maximum allowable stream velocity for separation of liquid droplets of a specified size occurs when the droplet imparts a drag force equal to the gravitational force. The maximum allowable velocity fixes the knockout drum diameter.

Since the drag force depends on particle diameter, the maximum allowable vapor velocity depends on the maximum size liquid droplet which can be burned in the flame. From Ref. 12, the relationship between liquid drop diameter and its terminal velocity is given by:

$$U_t = \sqrt{\frac{4Dg(\rho_l - \rho_v)}{3\rho_v C}} \quad (4.16)$$

where

D = maximum allowable droplet diameter, ft

ρ_l = liquid density, lb/ft³

ρ_v = vapor density, lb/ft³

U_t = terminal velocity of liquid droplet, ft/sec

g = gravitational acceleration constant = 32.174 ft/sec²

C = drag or friction factor (dimensionless)

The maximum allowable droplet size to be admitted to the flare can be estimated from experimentally determined burning rates (Ref. 71) but is normally chosen arbitrarily (Refs. 12 and 13). A typical value is 150 μ m. For removal of particles larger than 150 μ m, Eq. (4.16) reduces to:

$$U_t = 0.145 \sqrt{\frac{\rho_l - \rho_v}{\rho_v (C)}} \quad (4.17)$$

This basic equation is widely accepted for all forms of entrainment separation (Ref. 12).

The drag coefficient, C , corresponding to a given droplet diameter is obtained using an empirical correlation developed by Lapple and Shepherd (Ref. 70). The following equation approximates the experimental data to within $\pm 5\%$.

$$C = \sqrt{\frac{24}{Re} \left(\frac{24}{Re} + 4.5 \right)} \quad (4.18)$$

where

Re = Reynolds number

$= \rho_v U_t D / \mu$ (4.19)

μ = gas viscosity, lbm-ft⁻¹-sec⁻¹

Since the (unknown velocity appears both in Eqs. (4.16) and (4.18), the velocity is determined using an iterative solution method. There is no convenient closed-form equation to express the terminal velocity explicitly in terms of system parameters which is sufficiently valid for the entire range of applicable conditions. The range of validity of the correlation is discussed in Ref. 70.

Having determined the maximum allowable vapor velocity corresponding to a given maximum droplet diameter, the knockout drum diameter can be determined. For a vertical knockout drum with a tangential gas flow inlet, the drum diameter can be determined using the following equation:

$$D_k = \sqrt{\frac{4Q}{3600 \rho_v \pi U_t}} \quad (4.20)$$

where

Q = vapor relief rate, lb/hr

D_k = knockout drum diameter, ft

ρ_v, U_t = as previously defined

Horizontal and vertical knockout drums are available in many designs, the main differences being in how the path of the vapor is directed (Ref. 12). In sizing horizontal drums, it is necessary to consider the volume of stored liquid which will obstruct part of the vapor path (depending on liquid level). A liquid holdup (residence) time of 10-30 min is suggested (Ref. 12).

Safety factors are frequently considered necessary in drum sizing (Ref. 69). Very large drums on the order of 10 feet in diameter and 40 feet long are frequently considered necessary (Ref. 69). Other safety considerations include auto-refrigeration cooling and maintenance of the liquid level (Refs. 12 and 63). Heating coils may be required in cold climates or in applications where auto-refrigeration may be a problem (Ref. 63). A high level alarm is required to prevent liquid accumulation with a low level alarm to prevent vapor entry into the liquid disposal or recovery system (Ref. 12). Since level control is of vital importance to prevent liquid entry into the flare and to ensure an unobstructed vapor path at all times, duplication of alarm and control devices is frequently recommended (Ref. 63). Knockout drums equipped with automatic pump out systems should also include a means of manually controlling the liquid level.

4.4.9 Thermal Radiation Hazards

Hazards to people who are working in the vicinity of flares and to process equipment are normally the principal factors which determine location of the flare and flare height. Thermal emissions from the flare are dependent upon flame geometry and luminosity and upon ambient conditions such as relative humidity, wind effects and solar intensity. Some disagreement exists in the estimation of luminosity from flames and design methods employed have generally tended to be conservative. Fundamental understanding of the nature of turbulent flames and even the causes for thermal (infrared) radiation from flames is currently not available, so that meaningful correlations to allow luminosity and flame geometry to be predicted have not been established. As a result considerable variation exists in the estimation of these parameters. Most methods ignore effects such as absorption of thermal energy by the atmosphere and convective heat transfer between the flame and the ambient air and therefore serve to predict upper limits for radiation intensity. This is important

from a manufacturing cost standpoint but not from a safety point of view as long as current practice of estimating flare emissions is continued. Methods of current practice are described briefly in this section.

The principal design equation used in estimating thermal emissions assumes spherical emission of radiant energy from a point source (Refs. 12, 13, 14 and 30).

$$K = \frac{FQ}{4\pi D^2} \quad (4.21)$$

where

- K = radiant heat flux, Btu/hr-ft²
- Q = total heating rate of flame, Btu/hr
- F = the fraction of the total heat generated which is released as radiant energy
- D = distance from the point of emission, ft

The emissivity factor, F, may be estimated from Planck's law (Ref. 71) or empirical correlation (Ref. 13) but is usually adjusted from literature values (Refs. 12, and 72). Emissivity is believed to result from: (1) hot CO₂ and H₂O which emit in the near infrared, and (2) solid particles of carbon heated by the flame (Ref. 30). Emission from carbon particles is probably more important since emissions from CO₂ and H₂O are attenuated by CO₂ and H₂O in the air surrounding the flame. Flames of hydrogen and H₂S (which give H₂O only) and of methanol (which yields H₂O, CO₂) emit very little visible or infrared radiation (Refs. 16 and 72). Small-scale tests of hydrogen flames (Ref. 72) indicate that 98% of the radiation (from hot H₂O) would be adsorbed within the first 100 feet from the flame (Ref. 30) under normal atmospheric conditions.

Other evidence in favor of carbon emissions include (Ref. 16):

1. The intensity distribution is near that of a Planckian radiator
2. Emitted light obeys the Rayleigh law for small solid particles, and
3. The scattered light is polarized.

Even with the simplifying assumption of carbon as the predominant emitter, the emissivity would depend on a number of factors including particle size distribution, flame geometry and flame temperature. The usual approach (Refs. 4, 12, 13, 14), is to assume a constant value for K, based on adjusted experimental or literature values.

Experimental emissivity values for diffusion flames vary with burner diameter and carbon formation. Measured emissivity values increase with diameter to a value which is approximately constant (Ref. 72). This

Experimental emissivity values for diffusion flames vary with burner diameter and carbon formation. Measured emissivity values increase with diameter to a value which is approximately constant (Ref. 72)*. This upper limit is used for design purposes. Injection of steam, premixing with air and multijet designs reduce smoke, luminosity and thermal emissions (Ref. 12). However, smokeless burning with reduced emissivity is applicable in the use of Eq. (4.21) only for reduced flows. For full-scale emergency upsets, higher emissivity occurs. For example, when steam is used for smokeless flaring, common practice is to assume smokeless operation at 10% of the maximum flare discharge rate (Ref. 73).

Estimations of the flame boundary and wind effects are needed for the application of Eq. (4.21), in order to locate the origin of the emissions source ($D = 0$). Estimation of the flame boundary is complicated and methods exist only for the approximate calculation of the flame length. Therefore, usual practice (Refs. 12, 13 and 31) is to consider the emission of thermal energy as a point source near the midpoint of the flame axis. This method is considered to be adequate except for radiation calculations very close to the flare stack where view factors must be calculated to account for the approximately cylindrical flame geometry and the angle of orientation of the flame with respect to the object receiving the radiation (Ref. 30). Wind effects are normally considered separately.

An empirical correlation (Fig. 4-2) is recommended for estimating flame length by API RP 521 (Ref. 12). Flame length is considered to be a function only of the total heat released from the flame. Actual flame lengths may vary by as much as 50% (Ref. 49), and this variation should be allowed in the design method. Wind effects are considered separately.

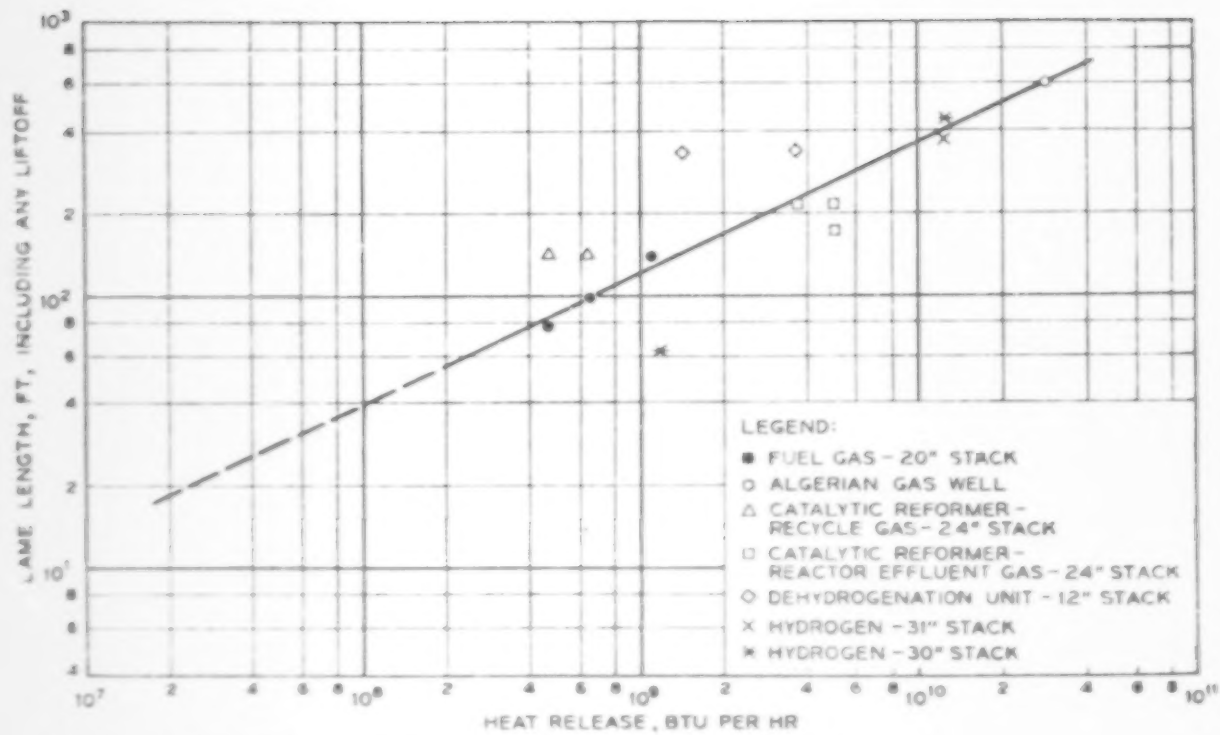
A design equation for estimating the length of turbulent flames is recommended by Craven (Ref. 71) based on the work of Hawthorne et al., (Ref. 74):

$$\frac{L-S}{d} = \frac{5.3}{C_t} \sqrt{\frac{T_F}{\alpha_A T_N} \left[C_t + (1 - C_t) \frac{M_s}{M_n} \right]} \quad (4.22)$$

where

- L = flame length, ft
- S = the height of the breakpoint from the nozzle, ft
- d = nozzle diameter, ft
- C_t = mole fraction of the nozzle fluid at the flame boundary
- T_F = adiabatic combustion temperature, °R
- α_A = the ratio of number of moles of reactants to number of moles of products for a stoichiometric mixture
- T_N = temperature at the nozzle, °R
- M_s = molecular weight of the surrounding air
- M_n = molecular weight of the fuel.

* Also see page 78 of this report for values of this upper limit.



Note: Multiple points signify separate observations or different assumptions of heat content.

Fig. 4-2 - Flame Length vs Heat Release (Industrial Sizes and Releases)
(from API RP 521, Ref. 12)

This equation (4.22) is based partially on empirical correlation (Fig. 4-3). The correlation includes data for diffusion flames of CO, CO_2 , city gas, acetylene, H_2 and propane. The validity of the correlation for fuels other than these is unknown.

An exact analysis of the flame shape is not available because suitable models are not available for the eddy diffusivity and the burning rate in turbulent flames. The analysis is complicated by axial changes in temperature and concentration along the jet. Definition of the flame boundary is necessarily arbitrary. A number of previous theoretical treatments formulate the diffusion equation for a single gas. The theoretical equation is then modified by empirical or semi-empirical relationships which compensate for the effect of other factors such as changes of temperature along the jet (Ref. 75).

Experimental studies have shown fairly simple scale-up behavior for both laminar and turbulent flames. For a given fuel, laminar flame lengths become independent of velocity (resulting presumably from the appearance of a velocity term in the eddy diffusion coefficient) and, for a given fuel, the ratio L/D is approximately constant (Ref. 75). For Mach numbers greater than about 0.05 flames are shortest for fully developed turbulent flow (see Fig. 4-4). Thermal emissions at grade are correspondingly greater, and flame length for fully developed turbulent flow are sometimes used as an upper limit for flare stack design purposes (Ref. 14). Following Kent (Ref. 14), the length-to-diameter ratio approaches:

$$L/D = 118 \quad (4.23)$$

where

L = flame length, ft

d = discharge diameter, ft.

During plant upsets, flame lengths may reach several hundred feet and moderate winds of 20 to 30 mph result in increased hazards to certain areas occupied by workmen and structures downwind from the flare. Under these conditions, the assumption that the flame is a point source at or directly above the flare stack is unrealistic. Most design calculations described in the literature have allowed for wind effects by displacing the "flame center" and assuming that the flame length is unaffected by the wind.

The following method is based on experimental data of jets impinging into still air. The empirical equation for velocity as a function of axial distance is modified by the constraint that at some distance $l = L$, the jet velocity is zero (Ref. 12). From API RP 521 (Ref. 12):

$$U_a = 1.6 d_o U_o \left(\frac{1}{l} - \frac{1}{L} \right) \quad (4.24)$$

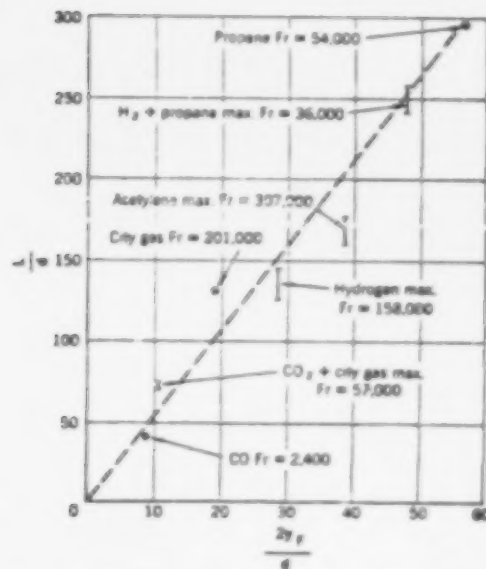


Fig. 4-3 - Plot of L/d (Flame Length/Nozzle Diameter) vs $2 \sqrt{F/d}$.
(from Hawthorne et al., Ref. 74)

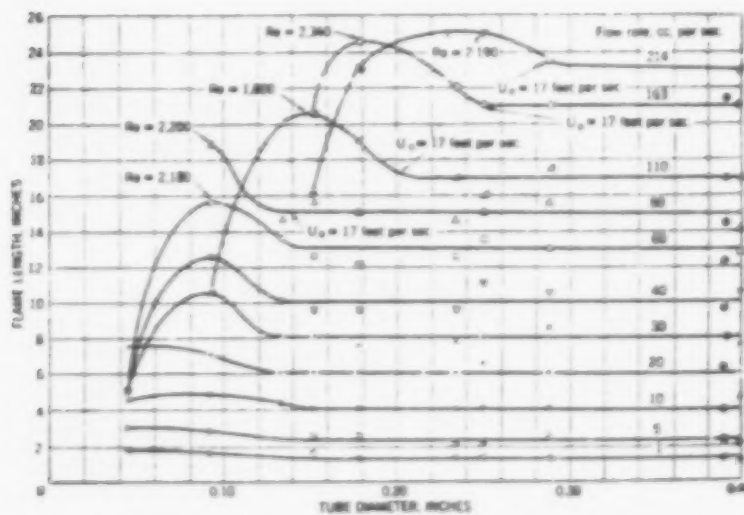


Fig. 4-4 - Diffusion Flames of City Gas in Air (from Ref. 74)

* y_F is the distance from the jet axis to the flame boundary. Thus $2 y_F$ = jet diameter.

where

- U_a = average axial velocity at l , ft/sec
- U_o = nozzle exit velocity, ft/sec
- d_o = nozzle diameter, ft
- l = distance along the jet axis from the nozzle tip, ft
- L = the effective flame length, ft. (The length is assumed to remain constant under the influence of the wind.)

Dividing the length L into M equal increments, the vertical, Y , and horizontal, X , displacements of the flame tip are calculated by the following equations from API RP 521 (U_w = wind velocity):

$$\frac{\Delta Y}{\Delta X} = \frac{U_a}{U_w} = 1.6\pi d_o \left(\frac{U_o}{U_w} \right) \left(\frac{1}{l} - \frac{1}{L} \right) \quad (4.25)$$

$$\Delta X = \Delta l \cdot \left[1 + \left(\frac{\Delta Y}{\Delta X} \right)^2 \right]^{-1/2} \quad (4.26)$$

$$\Delta Y = \Delta l \cdot \left[1 + \left(\frac{\Delta X}{\Delta Y} \right)^2 \right]^{-1/2} \quad (4.27)$$

then

$$X = \sum \Delta X \quad \text{and} \quad Y = \sum \Delta Y \quad (4.28)$$

Recent studies of thermal emissions include wind tunnel studies of wind effects on a diffusion flame (Ref. 77) which have been useful in the characterization of the flame boundary (Ref. 78). At least one experimental measurement of thermal emissions during flaring under controlled conditions has been made (Ref. 79) but is not yet available. Details of the effect of discharge velocity on flame length under full-scale flaring of hydrogen has been reported (Ref. 80).

The definitive recent work on the subject of flame boundary calculation and thermal radiation from flares appears to be that of Brzustowski and Sommer (Ref. 30). The design method includes the calculation of the heat flux and temperature rise in surrounding structures with and without wind cooling. The "point method" for estimation of thermal emissions is shown to be adequate (compared with the Battelle flare emissions study (Ref. 79)), given a reliable estimation of flame length and diameter and wind distortion.

According to this report (Ref. 30), a factor which may seriously affect operating safety is the uncertainty surrounding the calculation of flame emissivity. Design methods by Tan (Ref. 13) and a report by Reed (Ref. 35) give empirical equations from which estimates of the emissivity may be obtained. However, the best available design method is apparently still based on estimations based on literature values (Ref. 72).

In the flame boundary calculation of Brzustowski (Ref. 78), effects of the wind and plume velocity are combined. The flame boundary is considered to be the concentration envelope where the concentration is equal to the lean flammability limit. Flame propagation is assumed to be hydrodynamically controlled at high Reynolds numbers, according to the assumption of Chomiak (Ref. 81). The method of calculating the flame boundary is based on experimental observations of Hoehne and Luce (Ref. 77). A scaling parameter is used to account for the relative dynamic pressures of the jet and the wind:

$$R = \left(\frac{U_j}{U_w} \right) \left(\frac{\rho_j}{\rho_w} \right)^{1/2} \quad (4.29)$$

where

U_j = flare gas discharge velocity, ft/sec

U_w = wind speed, ft/sec

ρ_j = density of flare gas at discharge, lbm/ft³

ρ_∞ = density of ambient air, lbm/ft³.

Using this scaling parameter, the air molecular weight, M_∞ , and the fuel molecular weight, M_j , scaling of the vertical and horizontal coordinates of the flame tip and the lean concentration limit permits the use of correlations based on the study of Hoehne and Luce. Two cases arise. For

$$\bar{C}_L = C_L \left(\frac{U_j}{U_\infty} \right) \left(\frac{M_j}{M_\infty} \right) \leq 0.5$$

the flame tip coordinates are calculated from the following empirical relationships:

$$\bar{S}_L = 2.04 / \bar{C}_L^{1.03} \quad (4.30)$$

$$\bar{X}_L = \bar{S}_L - 1.65 \quad (4.31)$$

for $\bar{C}_L > 0.5$:

$$\bar{S}_L = 2.51/\bar{C}_L^{0.625} \quad (4.32)$$

$$\bar{X}_L = \bar{S}_L - 1.65 \text{ (for } \bar{S}_L > 2.35) \quad (4.33)$$

$$= f(\bar{S}_L) \text{ (for } \bar{S}_L \leq 2.35) \quad (4.34)$$

Where, in the above expressions:

$\bar{C}_L$ = dimensionless fuel concentration

$\bar{S}_L$ = dimensionless distance measured from orifice along the axis of maximum flare gas concentration

$\bar{X}_L$ = dimensionless horizontal displacement of the flame tip

$f(\bar{S}_L)$ = solution for $\bar{X}_L$ of the equation

$$\bar{S}_L = 1.04 \bar{X}_L^2 + 2.05 \bar{X}_L^{0.28} \quad (4.35)$$

The vertical rise of the flare tip is calculated from a correlation which applies along the axis of maximum concentration. The relationship used by Brzustowski is very close to that observed for a non-buoyant jet plume at high Reynolds number:

$$\begin{aligned} \text{where } \bar{Z}_L &= 2.05 \bar{X}_L^{0.28} \\ \bar{Z}_L &= \text{dimensionless rise of the flame tip above the flare} \end{aligned} \quad (4.36)$$

The computational procedure is described in detail by Brzustowski (Ref. 78) and a numerical example based on the procedure is given which includes sizing calculations for the flare stack (Ref. 30).

Absorption of thermal radiation by the atmosphere depends on the chemical nature of the emitting species. Thus, emissions of a given species in the flame, such as CO_2 and H_2O , are absorbed selectively by the same species in the atmosphere. Assuming blackbody radiation, attenuation by species in the atmosphere can be calculated. Hottel (Ref. 82) gives experimental emissivity values from which emissivity of the gas can be calculated given the temperature of the gas, the path length, L , and the partial pressure, P_w , of the absorbing species. Emissivity curves are given for CO_2 , water vapor, SO_2 , CO , and NH_3 . Curves for reduction in emissivity of CO_2 and H_2O mixtures resulting from spectral overlap are also given.

Brzustowski and Sommer (Ref. 30) give the following formula, based on the Hottel charts, from which atmospheric attenuation may be estimated:

$$t = 0.79 \frac{100}{r}^{1/16} \frac{100}{D}^{1/6} \quad (4.37)$$

where

t = fraction of K , Eq. (4.21), transmitted through the atmosphere

r = relative humidity, %

D = distance from flame to illuminated area, ft.

The above equation is strictly applicable only to a luminous hydrocarbon flame emitting at 2240°F, 80°F dry bulb ambient temperature, relative humidity more than 80%, and a distance from the flame of between 100 and 500 feet, but can be used to estimate the atmospheric attenuation under a wider range of conditions. In the case of flares, atmospheric absorption attenuates K by about 10 to 20% over distances of 500 feet.

Except when flaring gas streams which may contain toxic, odorous or noxious components, the stack height is determined by the height required to prevent thermal radiation intensity at ground level from reaching dangerous levels. Effects on operating personnel and plant and local processing and storage facilities are considered. For personnel, maximum intensity levels and exposure times given in API RP 521 (Ref. 12) are widely accepted. The maximum intensity level for continuous exposure without burns or blistering is 440 Btu/hr-ft².

Maximum intensity levels at grade (ground level nearest the flare stack) are normally calculated allowing a reasonable length of time for affected personnel to react and move to safety. A widely accepted (Ref. 36) intensity level at grade is 1000 Btu/hr-ft², which allows 30 seconds escape time to avoid pain, but numerous other standards are used or recommended in the processing literature. API RP 521 (Ref. 12) uses an intensity of 2000 Btu/hr-ft² at a distance of 150 feet from the base of the flare as the design criterion, but this level may be high. The various standards may result from the inexactness of the calculations for flame emissivity and total radiation. Maximum solar intensities are not usually considered but are significant (Ref. 35). At the latitude of Boston, solar radiation is on the order of 260 Btu/ft²-hr and may approach 300 Btu/ft²-hr in the Gulf Coast area.

Maximum allowable thermal radiation may vary with the proximity of equipment and storage facilities, the extent to which these can be protected, and the need for attendant personnel. Insulation and pressure relieving requirements of process equipment and storage facilities are described in API RP 521 (Ref. 12). Geometry and orientation of tanks or other equipment with respect to the flame and distance from the flare stack define the "view factor." This factor, the emissivity of the material of construction, and ambient conditions such as wind effects determine the maximum design temperature of surrounding objects. An upper limit which

may be useful for design purposes is the temperature reached by the object in free convection in the absence of wind cooling. This temperature may be calculated from the equation of Bruztowski and Sommer (Ref. 30):

$$K = 0.1713 \frac{T_s^4}{100} + \frac{0.21}{E_s} T_s - T)^{4/3} \quad (4.38)$$

where

K = average incident heat flux over the surface,
Btu-hr⁻¹-ft⁻²

T_s = surface temperature, °R

T = ambient temperature, °R

E_s = emissivity of the surface.

At a radiant density of 1000 Btu/hr-ft², and assuming a ground emissivity of 0.8, ground temperatures at the end of one minute can be as high as 195°F, reaching 315°F in about 20 minutes (Ref. 35). In operation under these conditions, a barren radial area about the flare is formed having a radius approximately equal to the flame length (Ref. 35).

SECTION V

RECOMMENDED DESIGN METHOD

General design criteria applicable to flare selection and sizing were discussed in detail in Section IV in order to establish the state-of-the-art foundation of existing design calculations. The purpose of this section is to summarize the sizing methods that are considered representative of methods being used at present. Along with Section IV, Refs. 2, 4, 5, 12, 13 and 14 are recommended for detailed explanation of the sizing calculations. A recent review article by Horton et al. (Ref. 17) provides a detailed qualitative description of auxiliary flare components. A review of Vanderlinde (Ref. 9) is recommended along with Section III of this report for a discussion of the flare stack components including methods of steam injection available for smokeless flaring.

The basis of the following discussion is an integrated disposal system including both an elevated and an enclosed ground (low level) flare. In the elevated flare, either air or steam injection is recommended as the preferred control method for smoke and particulates. Water injection is a less desirable means of control (Ref. 5).

In the integrated system, the low level flare is used for handling routine discharges to reduce noise, smoke, luminosity and thermal emissions. The elevated flare, with air or steam for particulate control is provided for handling full-scale emergency upsets. A "double seal" or "diversion seal," common to both flares is used to divert the waste gas stream from the elevated flare toward the low level flare (Fig. 15). Only during major upsets do gases pass through the upper level of the liquid seal and burn at the elevated flare.

Toxic, noxious or odorous gases or gases which yield hazardous combustion products should be collected in segregated piping systems and preferably disposed of by some means other than flaring. If flaring of such streams is required, these should be discharged directly into the elevated flare burner rather than into the diversion seal. Depending on stream volume, these streams can often be treated according to usual methods for segregation and disposal (Refs. 4 and 15).

5.1 Elevated Flare System

5.1.1 Required Design Information

The following information is recommended (Refs. 2, 4, 5, 12, 13 and 14). Much of this information can normally be obtained from relief valve sizing calculations.

1. Type of Material to be Flared
2. Average Molecular Weight, M

3. Percent Unsaturation
4. Lower (Net) Heating Value, $\hat{Q}$ Btu/scf
5. Specific Heat Ratio, $k = C_p/C_v$
6. Mass Flow Rate at Maximum Discharge, W lb/hr
7. Average Vapor Temperature, T °F
8. Flowing Pressure, p psig
9. Percent Toxic, Odorous or Noxious Gases

5.1.2 Flare Burner Diameter

Design parameters applicable to the calculation of the flare burner diameter include mass flow rate and discharge conditions, the type of flame holder used by the manufacturer, and density and heat capacity ratios which serve to define the sonic velocity in the fluid stream. Principal design considerations include pressure drop and flame stability considerations. Either may serve to define the diameter. Pressure drop rather than flow velocity is usually the controlling factor. The flare burner is usually limited to a pressure drop of 2 psig (60 in. H_2O).

To facilitate the sizing calculations, the maximum discharge rate is converted to the equivalent volume of air in scfh. The following orifice equation is used to calculate the burner diameter.

$$V_e = 1656 (K)(A) \sqrt{\Delta p} \quad (5.1)$$

where

V_e = volume equivalent flow rate, scfh

K = orifice factor, dimensionless

A = area of flare burner tip, ft^2

Δp = allowable pressure drop at tip, in. H_2O

The orifice factor K is normally about 0.9. The orifice factor and the effective internal tip area are somewhat variable depending on the flare design and manufacturer.

Maximum Discharge Velocity: The sonic velocity is determined by assuming perfect gas behavior (Refs. 2, 12, 13, 14 and 83) according to the following equation:

$$V_a = \sqrt{g_c KRT/M} \quad (5.2)$$

where

V_a = the acoustic velocity, or velocity of sound in the fluid,
ft/sec

g_c = dimensional constant, 32.17 lb-ft/lbf-sec²

K = ratio of specific heats, C_p/C_r

R = gas constant, 1546 ft-lbf/^oR-lb-mole

M = average molecular weight

The maximum discharge velocity for flame stability depends somewhat on the design of the flame holder and the height of the flare pilots above the flare tip. A maximum vapor velocity of Mach 0.2 is frequently recommended (Refs. 2, 12, 13 and 14). Discussions with flare vendors indicate that higher design velocities may be acceptable in some cases, but this figure seems to be a safe design basis. If this velocity is exceeded in Eq. (5.1), the pressure drop of the tip should be reduced accordingly.

Pressure losses in the flare seal, riser, entry and drums may also require a reduction in vapor velocity depending upon the available flowing pressure of the vent stream. For convenience, the pressure losses from these components is commonly expressed in terms of corresponding loss in velocity head (Refs. 83 and 84). For air under turbulent flow conditions, the equivalent length of pipe (in pipe diameters) is approximately equal to the velocity head loss multiplied by a factor of about 55. Pressure losses from the various flare components are summarized in Table 5-1.

Water Seal and Flame Arrestors: Water seals and flame arrestors are discussed in detail in Section 4.4.6 dealing with flare safety. For purpose of the present discussion, selection rather than sizing criteria are significant in determining the pressure drop. It is the result of this study that flame arrestors of conventional design are unacceptable because of their tendency to fill with solids and become plugged. Either water seals or flame arrestors are required when flammable mixtures are being flared, but a water seal is normally included in all flare systems as a precautionary measure.

Disentrainment or "Knockout" Drum: A disentrainment system is required whenever the dewpoint of the flared stream is higher than ambient temperature. A variety of designs have been employed for liquid disentrainment. These may be either vertical or horizontal and may be combined with the water seal. In some cases, a sloped piping arrangement with a drain at the lower end has been found adequate for removal of small amounts of liquid. Typically, liquid removal requirements are difficult to determine and a separate drum is installed between the flare stack and header, located external to the flare stack.

Table 5.1
PRESSURE LOSSES IN ELEVATED FLARE SYSTEM

Component	Equivalent Pipe Configuration	Velocity Head Loss **
Flare Tip	Orifice	Equation 5.1
Fluidic Seal	Orifice	Equation 5.1
Flare Riser	Equivalent Length of Straight Pipe	—
Molecular Seal	2 to 3 Close Return 180° Bends	3.0-4.5
Knockout Drum	1 Close Return 180° Bend	1.5
Water Seal*	1 Close Return 180° Bend and Depth of Diptube Immersion	1.5

* If the temperature of the vent gas is significantly higher than ambient, a material and energy balance on the water seal is required to determine the final temperature and the mole fraction of water in the flared stream.

** Units in equivalent pipe diameters. See Refs. 83 and 84 for details.

Knockout drum design and sizing criteria are given in Section 4.4.8. Reference 63 is recommended for a qualitative discussion of the knockout drum as it affects operating safety. Drum location, liquid holding capacity, pump capacity, other equipment requirements and a discussion of sizing methods are given in No. 10 of Ref. 2. For purpose of the pressure drop calculation, the drum is approximated by a close return 180-degree bend (Table 5-1).

5.1.3 Utility Requirements

Steam and Air Requirements: Either steam or air is required for flaring most gaseous hydrocarbons other than components such as methanol, carbon monoxide, hydrogen sulfide and methane or natural gas which burn smokelessly. Discussions with flare manufacturing firms indicate that steam requirements commonly cited (Refs. 2, 12 and 13) may not be suitable for design. The following empirical guideline is suggested for use:

$$W_{St}/W_{Hc} = \alpha - 10/M_w \quad (5.3)$$

where

W_{St}/W_{Hc} = steam-to-hydrocarbon mass ratio

M_w = average molecular weight of flared gases

α = empirically determined parameter dependent on the type of material being flared

For paraffins heavier than propane, $\alpha = 0.50$. For olefins, $\alpha = 0.60$. Other variables include nozzle design and point of injection. Because of these variables, steam utilization predicted by Eq. (5.3) may vary by $\pm 25\%$. Required steam pressure is at least 10 psig at the point of discharge.

Air requirements for smokeless burning are somewhat higher. For paraffins, the recommended value for α is 0.55, increasing to 0.69 for olefins. For forced draft flares, blower requirements are about 0.8 hp for each 1000 lb/hr of gas flared.

As mentioned previously (Section 4.3.3), use of water to control particulates is not recommended because of flame quenching, limited turndown, wind effects and other problems. Water requirements are also fairly high: 1.0 to 1.2 lb water are required for each pound of hydrocarbon gas.

High Pressure Hydrocarbon Streams: Hydrocarbon streams having pressures greater than about 2 psi may be burned smokelessly by means of special flare tip designs which increase air-fuel mixing. This is a rather specialized application and design criteria are not generally available except as they may apply to specific flare tip designs.

High pressure hydrocarbon jets of oil field or production gas may also be used instead of steam to achieve smokeless burning. Discussions with flare vendors indicate that gas requirements are extremely high. For example, approximately twice as much natural gas as propane is required to burn the propane stream smokelessly. The gas requirement for propylene increases by about another factor of two. The application of gas-assisted smokeless flaring is therefore limited to those applications in which the gas stream has no recovery value.

Vapor Purging Requirements: Safety considerations relating to vapor purging were discussed previously in Section 4.4.2. Purge gas requirements are normally based on the amount of gas flow required to prevent explosive mixtures in the flare stack, but another consideration is maintaining a stable flame (Ref. 2). The approach used will vary with the requirements of the system.

Husa (Ref. 62) has given the following empirical correlation to estimate the velocity required for prevention of explosive mixtures within the flare stack:

$$V = \left[\frac{0.022}{H-h} \right] \left[\frac{6}{X} \right]^{0.64} \left[\frac{28}{M} \right]^n \left[e^{0.16D} - 0.96e^{-0.16(D-M)} \right] \quad (5.4)$$

where

- V = purge gas velocity, ft/sec
- H = height of flare stack, ft
- h = protected length of stack, ft (typically H - h ≥ 25 ft)
- X = concentration of oxygen at the explosive limit, mole %
- M = molecular weight of purge gas
- D = flare tip diameter, in.
- n = dimensionless constant characteristic of the stack diameter

The exponent n is approximately unity for most stack diameters:

Diameter (in.)	Exponent n	Diameter (in.)	Exponent n
4	1.00	16	1.18
6	1.30	18	1.10
8	1.40	20	1.00
10	1.40	22	0.91
12	1.34	24	0.82
14	1.27		

Discussions with flare vendors indicate that the preceding equation should be used cautiously for flare diameters larger than about 24 inches.

In general, vapor purging requirements will vary with the type of gas being flared and the nature of the purge gas. Auxiliaries such as molecular and fluidic seals (Figs. 3-8 and 3-9) allow purge gas requirements to be reduced by 90% or more. Inert gas generators available from flare manufacturers can further reduce fuel required for purging by combustion of fuel gas at stoichiometric air-to-fuel ratio to produce a mixture of N_2 , CO , CO_2 and H_2O at approximately 11 times the original fuel gas volume.

5.1.4 Flare Height

Design considerations applicable to the calculation of flare height include thermal emissions and dispersion of gaseous emissions. Separate calculations are required for heat and dispersion. The larger result is used as the flare height. Noise and visible emissions calculations are performed as a check according to procedures described in Section 4.3.2. In some cases, these calculations may require an upward adjustment of the flare height.

Thermal Emissions: Factors affecting thermal emissions include flame length, wind effects and available unoccupied radius from the base of the flare stack. The basic design equation is that given as Eq. (4.21) of this report. The applicable design equation assumes spherical spreading of thermal emissions from an assumed point source. Experimental measurements (Ref. 30) show that the assumption of a point source or "flame center" is valid for distances greater than about three flame lengths from the flare stack. Closer to the stack, the point source model is too conservative, but serves as an upper limit for design purposes. Rearranging Eq. (4.21), the distance, D , required for reducing thermal intensity below the safe limit defines the stack height:

$$D = \sqrt{\frac{FQ}{4\pi K}} \quad (5.5)$$

where

D = safe distance from the point of emission, ft

K = maximum allowable radiant heat flux, $Btu/hr-ft^2$

F = the emissivity factor

Q = total heating rate of the flame, Btu/hr

Commonly accepted values for K are $1500 Btu/hr-ft^2$ for human exposure and 3000 for equipment exposure including view factors but ignoring atmospheric attenuation (see Section 4.3.1).

Emissivity factors are chosen which correspond to the flame under conditions in which smoke suppression is not used. Typical sources are Refs. 12, 13, 30, 67 and 68. Emissivity values from the sources are summarized on the following page:

<u>Component</u>	<u>Emissivity</u>
CO or low Btu gas	0.05
H ₂	0.075
CH ₄	0.10
C ₃ H ₈ and most paraffins	0.13
C ₃ H ₆ and most olefins	0.15
C ₄ H ₆ and hydrocarbons with M > 100	0.20

Factors which are somewhat variable and which determine the center of emissions for use in Eq. (5.5) are flame length and wind effects. Wind speed is frequently arbitrarily chosen as 30 mph for the design calculation. Given this wind speed and assuming highly turbulent flow under maximum discharge conditions, a number of semi-empirical expressions are available for locating the flame center. These are given in Refs. 12, 13, 14, 30, 70 and 71).

If justified by potential economic savings, comparison of several methods may serve to allow a basis for selecting the least expensive alternative, but the approximate nature of the calculations prevents an estimate of accuracy of any of these. Thermal radiation calculations used by flare manufacturing firms and chemical manufacturers contacted differ considerably and are frequently proprietary. Thus, it is not possible to summarize these in a single method. The following adaptation (Ref. 2) of a method described by Kent (Ref. 14) is representative in terms of the complexity of the calculations involved and the factors considered:

$$L_f \approx 120 D \quad (5.6)$$

where

L_f = flame length, ft

D = flare tip diameter, ft

For wind effects, tilting of the flame through an angle θ displaces the flame center:

$$\theta = \tan^{-1} \frac{V_w}{V_e} \quad (5.7)$$

where

V_w = velocity of wind, ft/sec

V_e = flare discharge velocity, ft/sec

θ = the angle of inclination of the flame, in degrees from the normal

The axial distance along the flame from the top of the flare stack to the flame center is chosen somewhat arbitrarily in the various design methods described. Some fraction of the flame length is typically chosen. In the absence of wind effects, the difference between the effective emission height, Y , and the stack height, H , is approximately (Ref. 12):

$$Y - H = L_F/2 \quad (5.8)$$

Wind increases the required stack height by reducing the effective emissions height and shifting the flame horizontally (Ref. 2):

$$X_1 = \sqrt{R^2 - [H + (Y - H) \cos \theta]^2} + (Y - H) \sin \theta \quad (5.9)$$

where

$$R = \sqrt{H(H + L_F)}$$

X_1 = the required safe distance from the base of the flare stack, ft

L_F, H, Y, θ as previously defined

If the available space at the flare location is known, the stack height required from thermal emission considerations can be calculated directly from Eqs. (5.6 through 5.9). A minimum safety boundary of at least 100 feet (Ref. 2) or approximately equal to the flame length is recommended.

Flare Height Dispersion Calculations: Flare height calculations for dispersion of gaseous emissions were discussed in detail in Section 4.3.7. In most cases, methods of calculation will be specified by local air pollution control agencies. The dispersion calculations given in Section 4.3.7 therefore serve only to illustrate some typical methods. Numerical examples illustrating the application of several of these methods are given in Refs. 2 and 12.

5.1.5 Supporting Structures

Elevated flare systems are usually supported by guy wires or derricks (Ref. 5). The type of support required affects foundation and piping costs and must be specified in the design. In general, self-supporting flares are feasible when stack heights are less than about 40 feet. Flare stacks between 50 and 100 feet high may be supported by guy wires, while stacks taller than 100 feet usually require a supporting derrick (Ref. 5). More complete guidelines are given in Ref. 2, as discussed in Section 3.1.4.

5.1.6 Auxiliary and Control Components

Flare auxiliaries typically include steam ratio control, flame front generators and pilot ignition systems, purge gas generators and control systems. Other controls may be required for forced draft and other more specialized disposal systems including blower and damper controls for

air-to-fuel ratios. Auxiliaries and controls are discussed in more detail in Section 3.1.3 of the present report and in Ref. 2.

Because of the requirement that flare systems must operate during emergencies such as power failure, pneumatic (fluidic) control systems are becoming increasingly popular for large elevated flare systems. For example, fluidic control of steam for smokeless burning is now available from one flare vendor. A new ignition system developed by Flaregas Company uses a flint generated spark to ignite the pilot flame, rather than electrical discharge, but the reliability of this system is not known (Ref. 2).

Ignition systems and pilot burners are available in complete units furnished by flare manufacturing firms. Typically, fuel gas and air are premixed and ignited by a spark. The flame generated is then "shot" by pressure to the pilot burner(s) over distances up to about 1000 feet (Ref. 2). Ignition systems presently require manual (push button) ignition, although automatic thermocouple alarm systems are available which have the capability to detect pilot flame extinguishment. Either instrument air or venturi inspiration are useful for air supply. Air and fuel premixing is controlled manually. Filtration and drying systems for air and fuel are normally recommended (Ref. 2). The ignition and pilot system should be fully specified in the sizing stages of design because provisions for locating the ignition system and controls must be made. Location of the ignition panel depends on flare stack height and distance with which pilot ignition can be accomplished reliably with a specified system.

Controls are also recommended (Ref. 63) for major auxiliary components such as the water seal or diversion seal and knockout drum as discussed in Section 4.4.3 and Ref. 12.

5.1.7 Endothermic Flaring - Low Btu Gas Streams

Flammability limits and heating value requirements are actually somewhat variable, depending on factors such as burner diameter and gas velocity (Ref. 1). At present, regulations for flaring gas streams seldom include guidelines to prevent the practice of flaring streams which will not burn. This requirement must therefore be self-enforced.

A lower (net) heating value of between 200 to 250 Btu/scf is normally considered adequate for flaring (Ref. 1) without additional heat inputs. Gas streams having heating values between about 100 and 200 Btu/scf can be flared provided that additional fuel is added to increase the heating value to the required minimum (Ref. 2). Gas streams with heating values less than about 100 Btu/scf are probably better suited to disposal by direct incineration.

Heating values may be calculated by standard methods found in furnace handbooks such as (Ref. 1). Flammability limits for individual components can be found in references such as Refs. 41, 42 and 43. Methods of estimating flammability limits of gas mixtures are given in Refs. 71 and 74.

5.2 Low-Level Flare

Low-level flare systems are a relatively new development. As a result, much of the information relating to design and performance is proprietary.

The diameter of a low level flare will be approximately 18 times larger than an elevated flare of conventional design. This observation is based on discussions with flare vendors (Ref. 10) and is based on performance comparisons between an eight inch elevated flare burner and a 12 foot diameter low-level flare, both designed for capacities of 25,000 lb/hr. Low-level flares are nominally sized for combustion rates in Btu/hr.

The height of low-level flare systems is determined by the height of refractory required to enclose the flame. The flare height is therefore strongly dependent on the type and number of discharge nozzles and their elevation within the flare.

SECTION VI

SAMPLING AND ANALYSIS TECHNIQUES

The sampling and analysis of flare combustion products are necessary to determine both the nature and amount of flare emissions and the efficiency of a flare as a combustion device. However, flare systems - especially elevated flares - present some very difficult sampling problems. As a result, very little emission data are available from flares. This section will discuss some of the problems of flare sampling, techniques used to sample flares, and some of the methods of gas analysis. Also discussed will be the measurement of air pollutants by remote sensing devices. While these methods are still generally in the development stage, measuring emissions from flares would be ideal by this technique since it eliminates the need for sample extraction.

6.1 Present Sampling Practices and Problems

An elevated flare presents almost impossible sampling conditions. Sampling of a stationary source is done to determine the concentration and characteristics of the contaminants, the mass rates of emissions as well as the efficiency of the device for reducing emissions. Flares present problems not only in just physically obtaining a sample but also in determining the mass rates of emissions and thus the efficiency.

To obtain a sample from an elevated flare, a probe must be inserted into the plume of a flare above the flame. Since the flame of just a medium sized flare can easily reach 500 feet, the logistics of obtaining a sample becomes formidable. Moreover, because of the heat and radiation of the flame, equipment and personnel must be located at a safe distance from the flare. To further complicate matters, the flame is never still, moving continuously because of wind and convection effects. This makes locating the plume of the flare difficult at best. Also since even small flares have very large capacities, any field tests will of necessity require very short sampling times, less than a minute, and a limited number of tests. These time constraints, added to the difficulty of obtaining a sample, makes it hard to obtain good reproducible data.

An additional problem of sampling elevated flares results from the fact that these flares discharge to the atmosphere before igniting. Combustion air is provided by the ambient atmosphere. The concentration of combustion products in the plume of a flare cannot be related to the mass rate of emissions without estimating or measuring the dilution of the plume with combustion air. At present there is really no good way to test for flare emissions. Until remote sensing methods are developed which require no sample extraction, flare emission testing will remain troublesome and expensive.

Because of these sampling problems and the intermittent nature of most flaring, only a few tests of flare emissions have been attempted and these

tests were mainly on small flares. Published results were found for only one elevated flare emission test (Ref. 31). Generally the data on the few flare tests completed are not published and are considered proprietary. The purpose of most tests was to determine the type and concentration of emissions. Little if any work has been done to determine the mass rate of emissions or the efficiency of the combustion process.

Discussions with vendors and flare users indicate that the sampling of elevated flares has usually been done using either cranes, derricks or scaffolding to reach the plume. However, because of sudden movements of the flame, care must be taken to protect both equipment and personnel. Samples have been taken either with stainless steel probes or evacuated grab samplers. The entire sampling train should be heated in the case of a probe to prevent condensation of water or heavy hydrocarbons while sampling.

In one test helium was injected into the gas before flaring and used as a tracer to measure plume dilution. Helium is inert during the flare combustion and its background atmospheric concentration is essentially constant. If one assumes that the diffusion and turbulent mixing of helium is the same as the other combustion products, the dilution of the plume by atmospheric air is linked to the concentration of helium in the plume. The concentration of the combustion products in the plume can then be related to the mass rate of emissions. In this test the helium concentration of the sample was analyzed by mass spectroscopy.

Sampling from a forced draft flare, while presenting many of the same problems as an elevated flare, is somewhat easier. The forced draft flare provides a stiffer flame and good outlet velocity which reduces the movement of the flame in the air and makes sampling easier. Also generally the forced draft flare is not nearly as tall as an elevated flare making obtaining the sample simpler. Low-level ground flares present much less of a sampling problem. The enclosure forms, in effect, a stack in which all the exhaust gases are directed. Thus standard stack sampling methods can be used. In some of the larger ground level flares, sampling ports have been built into the enclosure.

6.2 Analytical Techniques

The main emissions of interest in flare combustion are unburned hydrocarbons, partially oxidized hydrocarbons, carbon monoxide, nitrogen oxides and if sulfur is present in the waste gases sulfur dioxide. The analysis of carbon dioxide, while not a pollutant, is necessary to determine the efficiency of the combustion process. Information is given below on the existing analytical methods for these emissions and the commercial instruments which have been developed. No detailed procedures are included but references are given to sources of methods. Several reviews are available covering the subject of air pollutant analysis (Refs. 85 and 86). A particularly good review on general gas sampling and analysis techniques in combustion phenomena is presented by Lengelle and Verdier (Ref. 87). Much of the information presented below was obtained from Ref. 15.

6.2.1 Hydrocarbons

The gas chromatograph with a flame ionization detector (FID) is used to measure total hydrocarbons. The principle of the FID is based on the linear relationship of ion formation to the concentration of a given organic compound in a flame. The gaseous mixture is burned at a small jet and the change in electrical conductivity is measured. Response is a function of the number and type of oxidizable carbon atoms in a molecule. In general, there is only a small variation in the response of widely differing hydrocarbon types. However, oxygenated organic compounds have a lower relative response, decreasing with increasing oxygen content. CO_2 and CO , and inorganic gases show essentially no response. Instruments are available which use this technique to measure total hydrocarbons and methane separately and also carbon monoxide separately following its catalytic hydrogenation to methane (Ref. 88). Individual hydrocarbons are determined by gas chromatography using a flame ionization detector. ASTM D 2820 describes a method for determining C_1 to C_5 hydrocarbons.

6.2.2 Oxidized Hydrocarbons, Carbon Monoxide, Carbon Dioxide

The partially oxidized hydrocarbons respond to the FID and can be measured the same way as hydrocarbons. However, in most instances these compounds can be determined specifically by virtue of their functional group. Table 6-1 lists a number of approaches for several oxidized species which may be encountered. Carbon dioxide is most easily measured by the Orsat technique. Gas chromatographic and nondispersive infrared analyzers can also be used. In general gas chromatography is used for carbon monoxide measurements. For very low CO levels (less than 50 ppm) the CO must be converted to methane since the flame ionization detector does not respond to CO. Infrared spectrophotometry is also often used for spot CO analysis. Continuous monitoring for CO is usually performed by nondispersive infrared (NDR) analyzers. NDIR analyzers have the advantage of rapid response and good sensitivity over a wide range of concentrations.

6.2.3 Nitrogen Oxides

The applicability and limitations of the principal methods for determining NO_x are shown in Table 6-2. The two chemical methods are suitable for NO_x concentrations between 5 and 1000 ppm. When oxides can be determined without differentiation as NO_x , the phenoldisulfonic acid method of analysis is usually used. This is one of the few air pollution methods generally recognized to be accurate and reliable (Ref. 88). The instrumentation methods for determining NO_x include ultraviolet and infrared absorption, electrochemical sensor and chemiluminescence. The chemiluminescent is fairly new and is based on the reaction of NO with O_3 which results in the emission of light. This method is very sensitive and can be used to determine low levels of nitrogen oxides.

Table 6-1
METHODS FOR DETERMINATION OF OXIDIZED
HYDROCARBONS AND OTHER COMPONENTS (From Ref. 15)

Compound Determined	Method	Lower Limit (ppb)	Absorptivity (L/mol cm)
Aldehydes	Methylbenzothiazolone Hydrozone Spectrophotometric (650 nm)	20	50,000
Aldehydes and Ketones	Dinitrophenylhydrazine Spectrophotometric	40	27,000
Acrolein	4-Hexylresorcinol Spectrophotometric (605 nm)	20	17,000
Formaldehyde	Chromotropic Acid Spectrophotometric (570 nm)	20	19,000
Carboxylic Acids	Absorption-titration		1,100
Esters	Hydroxamic Acid Spectrophotometric (530 nm)	100	
Carbon Monoxide	Non-dispersive Infrared (NDIR)	1000	
Carbon Dioxide	NDIR Orsat	2000 0-5%	

Table 1-2
METHODS FOR NO_x (From Ref. 15)

Method	Principle of the Technique	Instrumentation	Applicability	Limitations
Phenyl disulfonic acid method (ASTM D 1608) (United & EPA)	$\text{NO}_x + \text{H}_2\text{SO}_4 \rightarrow \text{HNO}_3$ Phenyl disulfonic acid nitrate to produce yellow color.	Laboratory spectrophotometer at 400 mμ	Range: 5 to 1000 ppm for all nitrogen oxides except N ₂ O.	Not sensitive below 5 ppm.
Sulfanilic Acid method (ASTM D 2012) SAE J177	NO ₂ converts sulfanilic acid to diazonium salt. Salt couples with naphthyl to produce deep violet color	Laboratory spectrophotometers at 550 mμ. Continuous analyzers: Beckman AcraLyzer, Technicon Auto-analyzer.	Range: 0.01 to 4000 ppm. Specific for NO ₂ NO determined by prior oxidation. Useful for air and exhaust analysis. Faster than disulfonic acid method	Equipment somewhat more complex than for phenyl disulfonic acid method
Ultraviolet absorption method	NO ₂ has maximum at 400 mμ with absorptivity = 170 liters/mole-cm. NO is transparent above 230 mμ.	Continuous Analyzers: Beckman NMON Model 255 plus oxidation system.	Range: 10 to 6000 ppm. Determines NO ₂ directly. NO determined by prior oxidation.	NO is a reactive gas and can be partially lost unless precautions are taken.
Infrared absorption method	NO has band at 5.4 μ with absorptivity = 2 liters/mole-cm.	Continuous Analyzers: Beckman NRI Model 315A, Miro Safety/Analytance Model LIRA 200	Range: 10 to 6000 ppm. Determines NO directly.	Water vapor inter- feres and must either be con- stant, or pre- ferably removed.
Electrochemical Sensor	NO+NO ₂ permeate membrane on sensor and are electrochem- ically oxidized. Re- sulting current is proportional to NO _x concentration.	Continuous Analyzers: Dynamics EA-110 and EA-130 EnviroMetrics Model N-122 Theta Sensors Model LS-800-ANY	Range: 3 to 10000 ppm Models available for NO _x or NO ₂	SO ₂ interferes but can be eliminated or compensated for.
Chemiluminescence	The light resulting from the reaction of NO with ozone is measured with a photomultiplier. NO ₂ must be converted to NO to be measured.	Continuous Analyzers: Thermo-Electron Corp. Bendix, Environmental Science Division REM, Inc. Model 642	Range: 0.01 to 10000 ppm	No known interferences

6.2.4 Sulfur Dioxide

Table 6-3 summarizes some of the important features of the principal methods in current use for determining sulfur dioxide. In general, sulfur dioxide measurement involves two problems: obtaining a valid sample, and eliminating interferences. Because of its reactivity, SO_2 is best captured by using bubblers. The method generally considered most specific for determining SO_2 is the pararosaniline method (Ref. 89). Since the method requires close attention, it is not as widely used as the conductivity or the coulometric techniques.

6.3 Long Path Remote Sensing Techniques

The absorption techniques for remote sensing are promising new methods now being developed which would be ideally suited for measuring flare emissions.

Resonance absorption by molecules and atoms is the basis of a well-established method for determining the concentrations of such species. Usually, a continuum background from a flash lamp or other light source is viewed by a spectorgraph through the sample of interest. Absorption of the continuum occurs at wavelengths corresponding to transitions between specific energy levels of the species, the degree of absorption being a function of the specie concentration in the energy state corresponding to the lower energy level of the transition.

An equivalent technique consists of monitoring the absorption of the beam of a tunable laser after propagation through the sample under study, as it is tuned over the spectral region of interest. The latter method has the advantage of a considerably increased sensitivity because of the increased photon concentration per unit wavelength interval of such a light source, while its small beam divergence is also an advantage for long path applications. Also, their narrow linewidth admits to better discrimination against background radiation and an increased spectral resolution. Such tunable light sources can be considered to have revolutionized spectroscopy and especially the application of spectroscopic methods to pollution monitoring. For example, tunable sources have made possible consideration of such techniques as resonance backscattering and resonance Raman backscattering monitoring as the basis for potential monostatic remote sensors of ambient atmospheric pollutants. However, it is variations of the resonance absorption method that admit to the greatest probability of success as monostatic remote pollutant sensors (Refs. 90 and 91). Several such variations are presently being given considerable attention. One method, termed the Differential Absorption and Scattering (DAS) method, consists of monitoring the radiation backscattered elastically by ambient particulate matter and molecules in the atmosphere. By tuning the laser both on and off an absorption line of the pollutant of interest one can directly obtain the specie concentration. Another scheme, a direct absorption method, involves monitoring the beam absorption after transmission of the beam, through

Table 6-3
METHODS FOR SO₂ (From Ref. 15)

Method	Principle	Instrumentation	Applicability	Limitations
Hydrogen Peroxide Titration Method (EPA method 3)	SO ₂ + H ₂ O ₂ → H ₂ SO ₄ Titration with base or Ba**	Laboratory Equipment: Absorber and titration units	Range: 0.01 to 100 ppm	Requires reagent additions.
Hydrogen Peroxide Conductometric Method	SO ₂ + H ₂ O ₂ → H ₂ SO ₄ Measure Conductivity	Monitors: Leeds & Northrup, AEROSCAN Wosthoff U3S ULTRAGAS ANALYZER Scientific Instruments, IDC 902-1 Scientific Instruments, SI-67	Range: 0.01 to 5 ppm	Interferences by salt aerosols and acidic and basic gases which may be eliminated by filters.
Electrolytic (Boulometric) Method	SO ₂ + Br ₂ + H ₂ O → 2HBr + H ₂ SO ₄ SO + I ₂ + H ₂ O → 2HI + H ₂ SO ₄ Br ₂ and I ₂ generated electrolytically	Monitors: Consolidated, TITRILOG Beckman Instruments, Model 906 Barton 286 SULFUR TITRATOR Phillips Instruments, Model PW 700 Atlas Electric Devices, Model 1200	Range: 0.01 to 5 ppm Monitors simple to operate and reliable for unattended service.	Interference by oxidizing materials, aldehydes, olefins, and hydrogen sulfide. Some interference can be eliminated by filters.
WEST-GAFK Colorimetric Method ASTM D 2914	Formation of dyestuff by reaction with bleached pararosaniline	Laboratory Equipment: Spectrophotometer Monitors: Atlas Electric Devices, Model 1500 Technicon Corp., AUTO ANALYZER	Range: 0.01 to 5 ppm Most nearly specific method for SO ₂	Procedure cumbersome. Continuous analyzer needs close attention.
Electrochemical Sensor	Oxidation in a membrane-covered cell	Monitors: Dynasences, SS-330 EnviroMetrics NS-200 Theta Sensors LS-800-AS	Range: 0 to 5000 ppm Simple to operate	NO and NO ₂ interfere slightly.

the medium of interest, to a remote retroreflector. Again readings are obtained while the laser is both tuned to and detuned from an absorption line of the specie of interest, which leads to a direct measurement of the pollutant concentration.

Comparison of DAS and direct absorption methods show that DAS provides ranging capability by time-of-flight measurement, spatial resolution and three-dimensional, single ended measurement capability. The direct absorption method is simpler in that many of the low-power laser and broad-band sources presently available can be used (Ref. 92).

A common limitation inherent in all the absorption techniques is a practical limit on the detection sensitivity caused by atmospheric turbulence. Turbulent transfer of heat from the earth to the atmosphere causes localized variations in the index of refraction of air. Collimated light passed through the atmosphere is subject to distortion by the attendant focusing-defocusing effect (Ref. 93). Beam spreading, destructive interference within the beam cross section, and beam deflection can result. In remote measurements turbulence can cause the beam to overfill the receiver and can cause the energy received to vary as a function of time. One way to avoid these problems is to complete a measurement in less than a millisecond (Ref. 94). An alternative is signal-averaging over an appropriate time interval.

Long path techniques have many challenges to offer researchers over the next few years. Among the more important are the development of tunable sources and methods of tuning, the measurement of absorption coefficients with sources actually used in the remote-sensing system, and the thorough evaluation of systems to establish their sensitivity and accuracy under real measurement conditions. Once these challenges are met, the remote sensing of air pollutants should become a useful tool (Ref. 92).

SECTION VII

FLARE LOADINGS AND EMISSIONS FOR VARIOUS INDUSTRIES

To determine the impact of flaring on industrial emissions it was necessary to develop data on the quantity and composition of material being flared in order to estimate emissions. During this study of flare systems we have found almost no published data on the amount of flaring for a particular process. In talking to flare manufacturers and users, we have also found that usually users do not keep detailed data on what or how much they are flaring. However, it was generally agreed that the individual plant production people have a fairly good idea of the quantity and quality of gases being flared. It was decided that the best way to obtain this type of information on an industry-wide basis was through a questionnaire survey of a number of different users in each of the major industries that utilize flares. From the results of the survey, estimates were made of total flaring rates of various industries and also of the impact of flaring on total emissions. This section discusses the results of this survey including the calculation of flare loadings and emissions.

7.1 Questionnaire Format and Circulation

The primary purpose of the questionnaire was to determine the quantity and composition of waste streams now being flared. In addition general information on the type and operation of the flare unit was also sought. A copy of the questionnaire, together with the cover letter, is included in this section.

The questionnaire was submitted for approval to the Office of Management and Budget (OMB) in April 1974. After some modifications of the questionnaire, final approval was received from OMB in September 1974.

The flare survey was circulated to the following industries: petroleum refining, chemical manufacturing and iron and steel making. Except for petroleum and gas production, these three industries are the main users of flares. The actual circulation was done by the industry's trade association: The American Petroleum Institute (API) for petroleum refining, the Manufacturing Chemists Association (MCA) for chemical manufacturers and the American Iron & Steel Institute (AISI) for iron and steel making. Working through the trade associations not only made distribution of the survey simpler, since their mailing lists were used, but also helped the response. Response was excellent from all three industry groups with about 75% of the surveys being returned.

7.2 Refinery Questionnaire Results

Through cooperation of the American Petroleum Institute (API), a task force consisting of 10 representatives of the petroleum industry was

Lockheed
MISSILES
& SPACE
COMPANY,
INC.

LMSC-HREC TR D390190

HUNTSVILLE RESEARCH & ENGINEERING CENTER • P. O. BOX 1103 • HUNTSVILLE, ALABAMA • 35807

USER SURVEY — EPA FLARE SYSTEMS STUDY
Contract EPA 68-02-1331

We are currently engaged in an Environmental Protection Agency (EPA) sponsored engineering study of flare systems for control of gaseous emissions from stationary sources. The objective of this study is to evaluate the potential of flaring for hazardous emission control. Our final report, which will be publicly available, will include an evaluation of present flaring practice and design methods, general cost data, and data on any air pollution problem that flares themselves may cause. The EPA plans to use this report as a guide for potential utilization of flares and as a basis for future research and development programs in flare technology. We are obtaining our information from the literature by contacting flare manufacturers and from this user survey we are circulating.

We believe that industrial users of flare equipment comprise an important source of information for this study. Of particular interest is determining what waste streams are now being flared and the amount of flaring that is occurring. We ask that you participate in this survey by supplying the information requested on the enclosed questionnaire. Your participation will be valuable even if you can only supply part of the information requested. The information you supply will be held confidential by LMSC through the report writing stage, then destroyed. Some of it may appear in tabular or statistical form in our report but without identifying your company.

We would appreciate your completing a separate copy of Sections II-IV for each flare unit. We can supply additional copies if needed. If you have any questions, please call us at (205) 837-1800 and ask for M. G. Klett, J. B. Galeski or S. V. Bourgeois. Please return this questionnaire to Lockheed Missiles & Space Company, P. O. Box 1103, Huntsville, Alabama 35807, Attention: M. G. Klett.

Your cooperation in participating in this survey will be greatly appreciated.

Sincerely yours,

S. V. Bourgeois

S. V. Bourgeois
Project Manager

Enclosure: (1) Survey Questionnaire

SURVEY OF USERS OF INDUSTRIAL FLARE SYSTEMS
Contract EPA 68-02-1331

Date _____

Section I - Plant Identification

1. Name and Location:

- a. Name of Company: _____
- b. Plant/Division: _____
- c. No., Street: _____
- d. City: _____ State: _____ Zip: _____

2. Person to contact regarding information contained in this report:

- a. Name: _____
- b. Department/Division _____
- c. Telephone: (Area Code) _____

3. Principal product(s) of this plant: _____

4. How many flare systems (individual stack/burners) do you have at this location? _____

(If two or more, please complete Sections II to IV for each system.
Additional blanks are enclosed.)

Section II - General Information

- 1. Flare identification (if more than one at location): _____
- 2. Name of process(es) generating waste gas stream: _____
- 3. Capacity of process(es) (lb/hr, b/d, etc.): _____
- 4. Is the flare operated principally to control (check applicable items):
 - a. Intermittent flow of excess waste gas _____
 - b. Continuous flow of waste gas _____
 - c. Odor nuisance _____
 - d. Toxic nuisance _____

- e. Emergency or abnormal process venting _____
- f. Other (please specify) _____
- 5. Description of waste stream fed to flare (Engineering Estimate Permissible):
 - a. Waste stream(s) being flared: _____
 - b. Average composition of waste stream being flared: _____
 - c. Average load to flare for each combustible constituent(s) (for intermittent flares average load over a year): _____ lb/hr.
 - d. Number of major dumps to flare in previous year: _____
 - e. Amount of gas flared/dump _____ lb or scf
 - f. Heating value of waste stream: _____ Btu/scf
- 6. Is the waste stream pretreated prior to flaring? _____
If yes, please specify: _____

Section III - Flare Information

- 1. What is the type of flare (check one)?
 - a. Elevated _____ Height (ft) _____
 - b. Ground Level _____
 - c. Burning Pit _____
 - d. Other (Please specify) _____
- 2. Flare Capacity (lb/hr) _____
- 3. Flare Diameter (inches) _____
- 4. Does the flare have the following auxiliaries (check applicable items)
 - a. Knockout Drums _____
 - b. Water Seals _____
 - c. Flame Arrestor _____
 - d. Purging _____ Type of Purge Gas _____
Purge Rate _____ lb/hr.

- e. Stack Seal _____
- f. Smokeless Burning _____ Water _____ Stream _____
- g. Automatic Control of Smokeless Burning _____
5. Do you monitor flare emissions? _____ If yes, please specify how:

Are these data available to us? _____
6. What problems have you had in keeping the system operable? _____
7. Name of manufacturer of flare: _____
Did the same company design and install the system? _____
If not, name of company(s) which did: _____

Date of Installation: _____

Section IV - Follow-Up

Would you be willing to discuss in more detail system performance, data, and design features through a telephone call or visit to your plant by one of our representatives? _____

If you have any questions, please call one of the people listed on the cover letter at (205) 837-1800. Please return this questionnaire to Lockheed Missiles & Space Company, P.O. Box 1103, Huntsville, Alabama 35807, Attention: M. G. Klett. Thank you again for your cooperation.

assembled in order to develop the information that was required. The task force knew of no actual measurements of quantity and quality data for flares. However, they agreed that personnel at many refineries could make reasonable engineering estimates of these data. It was decided to obtain this information by means of the survey from a relatively small number of representative refineries. The sample included 18 refineries, three each from six different geographical locations, operated by 11 different oil companies. The questionnaire was circulated to the refineries through the API.

Replies were received from 17 of the 18 refineries contacted. All replies have reiterated that the quantity and quality data were from engineering estimates since these data were not measured. Five of the refineries that replied, supplied information on the number of flares and design specifications but felt they could not make even engineering estimates on the quantity and quality of material being flared.

For the remaining 12 refineries that supplied estimates on quantity and quality, 11 estimates were reasonably consistent. However, one estimate was so large, an-order-of-magnitude greater than the previous largest estimate, that it was not used for estimating flare loading but is included in the tabulated data for completeness (Refinery 12).

The refineries contacted had previously been selected for study in a joint API-EPA refinery modeling program because it was felt that they formed a representative sample of the total United States petroleum industry. The 11 refineries on which flare data are reported include at least one from each geographical location. These refineries represent 4% of the total number of refineries in the United States. However, their throughput totaled 14% of the total United States throughput for the 1973-74 time period. While our sample included refineries of varying size ranges, refineries greater than 100,000 bbl/cd predominated.

Table 7-1 shows a summary of the reduced data for the 11 refineries. This table includes the number of flares, the sum of the flare loads for each refinery broken down by composition, the percent of the refinery throughput that is sent to the flare and the heat loss for each refinery computed from the heating value of the streams sent to each flare. Most of the quantity data were given for both 1973 and 1974. The numbers reported in the summary table are the two year average value. Normally flare loading is very intermittent with flare occurrences happening on the order of 8 to 10 times a year. The reported flare loadings are the two year averaged loadings reduced to a calendar day basis.

The amount of gas flared from each refinery ranged from 0.04 to 0.60% of the refinery's crude runs with an average of 0.19% for the 11 refineries. Applying this percentage to the total crude processed in the United States of 12,281,000 bbl/cd would indicate an amount of flaring from refineries for 1973 and 1974 of 7.2×10^6 pounds per calendar day or about 24,000 bbl/cd.

Table 7-1
SUMMARY OF REFINERY FLARE DATA

Refinery Number	No. of Flares	Design Capacity (Mlb/hr)	C ₁ (lb/cd)	C ₂ (lb/cd)	C ₃ (lb/cd)	C ₄ (lb/cd)	C ₅ (lb/cd)	Aromatics (lb/cd)	Olefins (lb/cd)	Paraffins (lb/cd)	Total Hydrocarbon (lb/cd)	H ₂ (lb/cd)	H ₂ S (lb/cd)	NH ₃ (lb/cd)	Other (lb/cd)	Total (lb/cd)	Refinery Throughput (bbl/cd)	% to Flare	Heat Loss (Btu/cd x 10 ⁶)
1	3	333	—	345	505	664	—	—	—	1,514	1,514	—	2,640	—	23,760	27,914	54,437	0.170	49
2	2	240	135,825	39,836	35,400	25,617	30,488	—	28,199	238,967	267,166	5,233	2,308	—	—	274,707	167,658	0.554	6,060
3	4	3,305	2,124	4,691	18,799	27,987	36,709	10,536	27,093	42,481	90,310	1,456	32	2	—	91,800	213,000	0.143	1,896
4	2	1,407	15,488	4,806	4,575	3,930	2,878	—	3,543	28,334	31,677	343	280	—	—	32,300	73,700	0.145	702
5	5	385	2,090	4,926	339	531	477	—	2,411	5,952	8,363	181	8,278	244	1,844	18,910	106,064	0.059	250
6	7	2,319	3,326	9,683	8,737	4,286	2,021	359	5,282	22,412	28,053	963	872	—	8	29,896	255,000	0.039	653
7	4	640	3,409	3,384	13,788	16,721	1,807	—	3,911	35,198	39,109	577	426	—	—	40,112	239,400	0.056	835
8	8	2,600	17,047	21,309	128,139	12,359	20,457	—	23,917	175,394	199,311	852	4,830	—	28,556	233,549	365,500	0.210	4,177
9	2	1,608	42,946	36,602	71,577	23,588	17,569	—	40,480	151,802	192,282	3,254	2,766	—	6,830	205,132	112,652	0.604	4,243
10	6	3,051	15,922	22,332	12,584	4,999	6,206	—	8,184	53,859	62,043	3,181	4,396	—	—	69,520	162,908	0.142	1,541
11	2	654	20,084	10,938	55,685	5,847	3,482	—	—	78,035	78,035	372	390	—	3,407	82,704	145,060	0.189	1,910
Total	45	16,564	258,260	158,852	350,128	126,529	122,094	10,895	142,820	844,148	997,863	16,412	27,218	246	64,905	1,106,644	1,899,419	0.193	22,316
12	8	18,701	213,928	167,131	1,244,001	864,345	80,223	—	—	2,569,638	2,569,638	—	—	—	—	2,569,638	306,590	2.781	52,446

The heat loss that flaring represents was calculated for each refinery and averaged nearly 20,000 Btu/lb. This would indicate a total heat loss from refinery flaring in the United States of 1.4×10^{11} Btu/cd. This represents about 0.6% of the total gas sold for industrial use in the United States for 1973 and 1974 (Ref. 95).

Figure 7-1 is a plot of the crude run versus flare loading for each refinery. The solid curve represents the simple average flare loading for these 11 refineries. While the flare loading generally increased with refinery throughput, the scatter of the data indicates that there are other parameters involved in flare loading other than refinery throughput. However, the average flare loading of these 11 representative refineries is probably a good indication of the average flare loading of the petroleum industry.

Ninety percent by weight of the total load to flares consisted of hydrocarbons. Hydrogen made up 1.6% of the load and hydrogen sulfide 2.6% with the remainder consisting of mainly water vapor and nitrogen. Much of the hydrogen sulfide flared was of low concentration in hydrocarbon streams. However, there were flares mainly in sulfur recovery units where streams containing hydrogen sulfide concentration of up to 50% were flared.

7.3 Impact of Flares on Refinery Emissions

In order to determine the impact of flares on refinery emissions not only data on the quantity and quality of gases being flared are necessary but also information is needed on the efficiency of flares as combustion devices and the nature and amount of flare emissions. However flare systems- especially elevated flares-present very difficult sampling problems. As a result, very little emission data are available from flares.

The only known published report of a field test on a flare unit was by Sussman et al. (Ref. 31). He reported the results of the test for a steam inspired type of elevated flare in the form of volume ratios:

CO ₂ :	Hydrocarbon	2100:1
CO ₂ :	CO	243:1

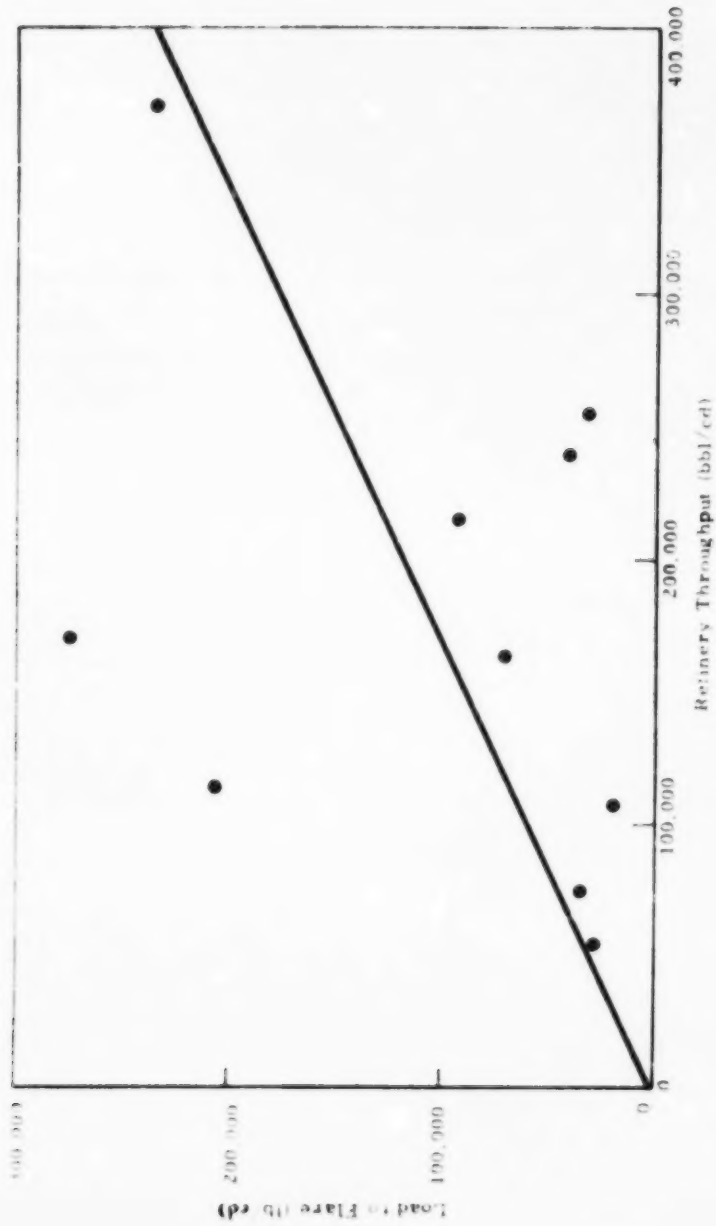


Fig. 7-1 - Crude Run vs Flare Loading

Calculations based on these data were made using the estimated quantity and quality data of the previous section in order to obtain an estimate of the total emissions of carbon monoxide and hydrocarbons caused by flaring. The calculations assumed a gas with three carbon atoms and a molecular weight of 42, the average molecular weight of the refinery gas being flared.

NO_x emissions were estimated from the data of Chase and George (Ref. 96) and SO₂ emissions were calculated from the total amount of sulfur being flared. Table 7-2 shows the calculated total emissions of hydrocarbon, carbon monoxide, nitrogen oxide and sulfur dioxide from refinery flares. Table 7-2 also shows the percent of the total refinery emission from each gas due to flaring. The total refinery emissions were estimated from refinery emission factors (Ref. 58) and base on average refinery runs for 1973 and 1974.

Table 7-2
TOTAL ESTIMATED EMISSIONS FROM REFINERY FLARES

Gas	Emissions (10 ⁶ lb/yr)	Percent of Total Refinery Emissions
HC	3.4	0.2
CO	6.5	0.1
NO _x	17.1	0.5
SO ₂	137.3	0.9

These numbers, based on engineering estimates of quantity and quality and a minimum of field testing, should be considered tentative. However, they do indicate that the average yearly emission from flares constitutes just a small fraction, less than 1%, of the average yearly refinery emissions. Total flare emissions over a year's time therefore probably only have a small impact on total refinery emissions. However, because of the intermittent nature of flaring, the majority of flare emissions are concentrated into just a few minutes of actual flaring. During this time four or five times the normal refinery emissions are released into the atmosphere. While design modifications for flares to suppress smoke formation has been largely successful, very little if any work has been done to suppress emissions resulting from unburned hydrocarbons and partial oxidation products.

7.4 Iron and Steel Mills Questionnaire Results

Through the cooperation of the American Iron and Steel Institute (AISI), the survey was distributed by the AISI to the major manufacturers of iron and steel in the United States. There are two types of gases that are flared in iron and steel mills, excess blast furnace gas and excess coke oven gas. Flaring is only done on an intermittent basis, usually to control line pressure, and generally the gases are scrubbed before flaring.

Ninety-nine percent by weight of the combustible blast furnace gas consisted of carbon monoxide. The remaining one percent consisted mainly of hydrogen and methane. Hydrocarbons made up 73% by weight of the coke oven gas, carbon monoxide 17%, hydrogen 9% and hydrogen sulfide 1%.

Replies were received for 61 blast furnace gas flares and 30 coke oven gas flares. Several of the replies received supplied information on the capacity and design specifications of the flares but felt that they could not make engineering estimates on the quantity and quality of material being flared. Quantity and quality data were given for 35 blast furnace gas flares and 20 coke oven gas flares. The replies represent 38% of the raw steel production capacity in the United States.

Table 7-3 shows a summary of the reduced data for the blast furnace flares and Table 7-4 for the coke oven flares. The table includes the number of flares, the sum of the flare loads broken down by composition and the heat loss associated with this flaring. The reported flare loadings are averaged yearly loadings reduced to a calendar day basis.

The weight of combustible gas flared from blast furnaces averaged 6.6% of the furnace's capacity. Applying this percentage to the total 1974 United States' capacity of 145.5×10^6 tons would indicate an amount of flaring from blast furnaces in 1974 of 5.3×10^7 pounds of combustible gases per calendar day. The heat loss that this flaring represented amounted to 2.5×10^{11} Btu/cd.

The amount of combustible gas flared from coke ovens averaged 0.4% of the ovens' capacities. Applying this percentage to the total iron and steel industry's coke capacity of 55×10^6 tons would indicate the amount of flaring from coke ovens in 1974 of 1.1×10^6 lb/cd. The heat loss that this flaring represented amounted to 1.9×10^{10} Btu/cd.

While the lost heating value of blast furnace gas that is flared is comparable to the heating value of the gas flared from refineries, the iron and steel industry has little alternative but to flare the excess gas. Blast furnace gas typically consists of 25% CO and the remaining inert gases. Therefore, the heating value of the gas is low, around 90 Btu/ft³, making it uneconomic to recover any that cannot be used immediately.

In addition to blast furnace gas and coke oven gas flares there were a few other flares reported from the iron and steel industry on miscellaneous processes including sulfur plants and an annealing plant. Table 7-5 gives a summary of the reduced data for these plants.

7.5 Impact of Flares on Iron and Steel Mill Emissions

While there have been no published report of field tests on blast furnace gas flares, the data of Sussman et al. (Ref. 31) for a refinery flare indicates greater than 99% complete combustion of hydrocarbons. Assuming a 99% efficiency for blast furnace flares, the emissions of CO from these flares in 1974 was 1.9×10^8 lb which is equal to about 1% of CO emissions from industrial processes.

Table 7-3
SUMMARY OF BLAST FURNACE FLARE DATA

No	Process Capacity (tons/day)	No. of Flares	CO (lb/cd)	H ₂ (lb/cd)	CH ₄ (lb/cd)	N ₂ and CO ₂ (lb/cd)	Total Combust. (lb/cd)	Heat Loss (Btu/cd x 10 ⁶)	Height (ft)
1	6,700	3	333,000	1,800	—	1,048,000	335,000	1,600	160
2	2,200	1	3,000	—	—	9,000	3,000	700	109
3	2,800	1	936,000	4,800	—	2,082,000	941,000	4,200	130
4	3,600	1	864,000	2,400	—	3,975,000	866,000	3,800	201
5	900	1	197,000	1,100	—	275,000	198,000	800	112
6	4,300	1	16,000	—	—	43,000	16,000	100	140
7	2,500	1	459,000	7,300	—	1,638,000	466,000	2,300	109
8	6,900	1	1,386,000	20,400	—	4,585,000	1,306,000	6,400	200
9	500	1	92,000	1,500	—	321,000	93,000	500	160
10	5,200	2	3,229,000	50,100	—	11,295,000	3,279,000	17,100	150
11	2,600	1	2,228,000	12,300	4,700	5,757,000	2,244,000	9,500	111
12	2,500	1	240,000	600	—	656,000	241,000	900	125
13	2,000	1	348,000	3,300	—	1,164,000	351,000	1,500	167
14	3,900	1	254,000	2,000	—	867,000	256,000	1,100	200
15	3,200	1	207,000	1,600	—	708,000	209,000	900	200
16	7,600	1	171,000	—	—	121,000	171,000	700	240
17	16,000	4	164,000	500	—	493,000	165,000	700	140
18	3,400	2	232,000	2,200	—	712,000	232,000	1,100	89
19	11,700	1	701,000	7,200	12,000	2,280,000	691,000	3,200	113
20	5,500	1	179,000	1,400	500	662,000	181,000	900	198
21	2,700	1	217,000	100	—	781,000	217,000	1,000	155
22	5,900	1	392,000	—	—	214,000	392,000	1,600	230
23	800	1	177,000	500	—	517,000	177,000	800	160
24	4,000	1	246,000	2,000	—	712,000	248,000	1,000	150
25	6,000	3	189,000	1,500	—	720,000	190,000	1,000	137
26	6,600	1	753,000	2,000	—	2,138,000	755,000	3,200	150
27	5,800	2	556,000	1,400	—	1,578,000	557,000	2,600	125
28	13,000	4	1,639,000	12,900	22,400	6,439,000	1,674,000	8,900	200
29	2,600	1	674,000	5,900	—	2,565,000	680,000	3,200	139
30	600	1	65,000	500	—	247,000	66,000	300	110
31	3,500	1	914,000	8,500	—	3,393,000	922,000	4,300	202
32	1,200	1	883,000	7,100	—	2,845,000	890,000	4,000	100
33	1,100	1	34,000	9,600	—	48,000	43,000	600	230
34	2,500	1	248,000	700	—	713,000	249,000	1,100	150
35	2,500	1	1,107,000	18,100	—	3,533,000	1,125,000	5,200	160
Total	152,800	48	20,233,000	191,300	39,600	66,034,000	20,431,000	96,800	154 (Average)

Table 7-4
SUMMARY OF COKE OVEN FLARE DATA

No.	Process Capacity (ton/day)	Hydrocarbon (lb/cd)	H ₂ (lb/cd)	CO (lb/cd)	H ₂ S (lb/cd)	N ₂ , CO ₂ , H ₂ O (lb/cd)	Total Combust. (lb/cd)	Heat Loss (Btu/cc × 10 ⁶)	Height (ft)
1	500	62,500	1,800	18,700	850	377,000	84,500	1,080	36
2	450	2,000	300	600	—	600	2,900	60	100
3	2,170	900	100	100	—	200	1,100	10	115
4	1,340	900	100	300	—	400	1,300	30	100
5	3,940	5,300	1,500	2,700	—	1,600	9,600	240	135
6	2,010	21,300	1,500	1,400	170	4,600	24,500	280	121
7	410	10,400	2,000	2,800	210	4,000	15,200	360	80
8	2,340	5,200	1,200	1,700	—	1,100	8,100	170	100
9	2,830	70,700	11,100	7,500	—	36,800	89,300	1,780	100
10	1,910	3,100	500	700	—	1,400	4,300	110	—
11	260	5,500	1,100	1,500	—	2,100	8,000	190	80
12	510	600	100	100	—	100	800	10	100
13	1,570	800	100	200	—	100	1,100	20	100
14	4,750	1,100	200	400	—	700	1,700	20	100
15	2,480	8,300	300	4,500	270	3,900	13,400	290	110
16	3,800	6,500	1,200	3,500	210	3,000	11,400	250	151
17	3,500	700	100	300	—	400	1,100	30	150
18	1,000	12,000	1,600	1,800	—	—	15,400	250	225
19	5,070	1,700	300	600	—	1,100	2,600	70	125
20	2,510	6,600	1,200	2,100	200	4,400	10,100	230	104
Total	43,350	226,100	26,300	51,500	1,910	443,500	306,400	5,480	112*

* Average

Table 7-5
SUMMARY OF FLARE DATA FROM MISCELLANEOUS IRON AND STEEL PROCESSES

No.	Process	Capacity (ton/day)	Hydro- carbon (lb/d)	H ₂ (lb/d)	CO (lb/d)	H ₂ S (lb/d)	Inert (lb/d)	Total Combust.	Heat Loss (Btu/d x 10 ⁶)	Height (ft)
1	Sulfur Plant	15	1,200	—	—	36,100	20,520	37,750	328	150
2	Desulfurization	94	—	HCN 2,530	1,120	16,847	9,630	20,500	240	206
3	Anneal Atmos. Gas	3,000	2	6	66		710	74	1	8
4	NH ₃ Destruction	87	—	NO _x 29	NH ₃ 29	SO ₂ 2,470	171,370	29	—	100

For coke oven flares, calculations were made for emissions of HC, CO, NO_x and SO₂ in the same manner as the refinery flares. Table 7-6 shows the results of these calculations along with the percent of the total emission from coking from each gas due to flaring. The total coke plant emissions were estimated from emission factors (Ref. 58) and based on 1974 coke production.

Table 7-6
TOTAL ESTIMATED EMISSIONS FROM COKE OVEN GAS FLARES

Gas	Emissions (10 ⁶ lb/yr)	Percent of Total Coke Plant Emissions
HC	0.4	0.2
CO	1.5	2.1
NO _x	0.7	5.8
SO ₂	4.8	0.9

These results, based on engineering estimates and a minimum of field testing, are tentative. However, as with refinery flares, they indicate that the emissions from coke oven flares constitute a small portion of the average yearly emissions from coke plants.

7.6 Manufacturing Chemists Questionnaire Results

Through the cooperation of the Manufacturing Chemist Association (MCA), the survey was distributed by the MCA to members likely to make use of flare systems. Replies were received for 75 different flare units. However, many of the questionnaires did not give information on the quantity and quality of gases being flared. Forty replies were received covering the manufacture of 15 different chemicals which gave data on the quantity and composition of gases being flared.

Table 7-7 shows a summary of the reduced data for these chemical process flares. The table includes the identification of the process, the capacity of the process, the sum of the flare loads broken down by composition and the heat loss associated with this flaring. The reported flare loadings are averaged yearly loadings reduced to a calendar day basis.

Most of the different chemicals for which flare loading data were reported included data from only one or two plants. Because of the scatter of the flare loading data from plant to plant, meaningful estimates of industry flaring loads can only be made by averaging the loadings for a number of individual plants. The only chemical in which flare loading data were available from a number of different plants was ethylene. However, the other data give a rough idea of the magnitude of flare loadings for these processes.

Table 7-7
SUMMARY OF CHEMICAL PROCESS INDUSTRIES FLARE DATA

Process	Capacity (lb/yr)	Hydrocarbon (lb/cd)	CO (lb/cd)	H ₂ (lb/cd)	N ₂ , H ₂ O, CO ₂ (lb/cd)	Other (lb/cd)	Total Combust. (lb/cd)	Heat Loss (Btu/cd x 10 ⁶)
Olefins								
Ethylene	964 MM	10,100					10,000	195
Ethylene	630 MM	44,650	1,100	1,670	2,580		47,420	660
Ethylene	500 MM	17,400			700	1300-H ₂ S	18,700	350
Ethylene	750 MM	10,100					10,100	155
Ethylene	830 MM	26,300		600			26,900	562
Ethylene	775 MM	48,000					48,000	960
Acetylene	325 MM	1,700					1,726	33
Aromatics	750 MM	7,900					7,900	157
Petrochemicals	2,000 MM	96,000					96,000	2,600
Petrochemicals	660 MM	300					300	5
Polypropylene	260 MM	55,200			20,000		55,200	476
Polypropylene	110 MM	2,500					2,500	37
Butyl Rubber	200 MM	36,000					36,000	650
Acetic Acid	110 MM	8,700					8,700	152
Acetic Acid	110 MM	7,900	19,800	39,600	11,900		67,200	455
Acetic Anhydride	160 MM	6,900	8,700		3,600		15,600	
Acetic Anhydride	140 MM	70,000	30,400	300	16,200		100,700	1,080
Adipic Acid	380 MM					9600-NO _x		
Acrylonitrile	365 MM					16-HCN	16	1
Acrylonitrile	350 MM					276-HCN	276	3
Ammonia	550 MM	40,600		13,500			54,100	1,680
Ammonia	660 MM					192-NH ₃	192	1
Ammonia	800 MM					4800-NH ₂	4,800	43
Alcohols	215 MM	16,300					16,300	335
Carbon Black	244 MM	3,600	30,300	2,900	430,000	650-H ₂ S	37,500	421
Phosphorus	9 MM	19	10,300	37	236		10,400	46
C ₂ S and S Recovery	73 MM	360				84-C ₂ S	444	9
NaHS	37 MM					10-C ₂ S	10	1
Aldicarb	53 MM	3,100				528-HCN	3,600	27
CO For Phosgene	70 MM	1,440					1,440	2
Oil Additive	342 MM	10,900					10,900	216
Storage and Loading								
Ethylene Loading	10 ⁵ lb/hr	12,000					12,000	243
Ethylene Storage	263 M	2					2	
Butadiene Storage	536 M	1,000					1,100	21
Ammonia Storage	40 MM					950-NH ₃	950	9
HCN Storage	200 M					480-HCN	480	2
Tank Car Loading		1,080			120		1,080	9
Azodrin	12 MM	96					96	1
Nudrin	6 MM	15			7-H ₂ C	10-HCN	32	1
Nudrin	6 MM				18	6-HCN	6	1

Data were received from six different ethylene plants representing 19% of the total U.S. ethylene capacity. The weight of the combustible gas flared by these plants averaged 1.3% of the capacity. Applying this percentage to the total U.S. 1974 capacity of 24×10^9 lb would indicate an amount of flaring from ethylene plants in 1974 of 8.7×10^5 lb/cd. The heat loss that this flaring represented amounted to 1.6×10^{10} Btu/cd.

7.7 Summary of Flare Loadings

From the survey results, flare loadings of combustible gases were calculated for four process industries: (1) petroleum refining; (2) ethylene production; (3) blast furnace operation; and (4) coke production. Table 7-8 summarizes the data for these industries.

Table 7-8
INDUSTRY FLARE LOADINGS AND HEAT LOSS

Industry	Industry Flare Loading (lb/cd)	Flare Loading as Percent of Capacity	Heat Loss (Btu/cd)
Petroleum Refining	7.2×10^6	0.19	1.4×10^{11}
Ethylene Production	8.7×10^5	1.3	1.6×10^{10}
Blast Furnace Operation	5.3×10^7	6.6	2.5×10^{11}
Coke Production	1.1×10^6	0.37	1.9×10^{10}

To estimate emissions from flares, information is needed on the efficiency of flares as combustion devices. Estimating emissions from very limited field test data on flares and using industry flare loadings from the survey results indicate that the average yearly emission from flares constitutes just a small fraction, less than 1%, of the average yearly industry emission. Total flare emissions over a year's time, therefore, probably only have a small impact on total emissions. However, because of the intermittent nature of flaring, most of flare emissions are concentrated into just a few minutes of actual flaring. During this time four or five times the normal industry emission are released into the atmosphere.

SECTION VIII

RECOMMENDED RESEARCH PROGRAM

8.1 Theoretical Analysis of Combustion Modifications Applicable to Flaring

8.1.1 Summary and Objectives

Because of the lack of present sampling capability and emissions data for elevated flares, other means of estimating gaseous emissions are required for evaluating proposed pollution control methods and regulations and for evaluating the applicability of current combustion technology to flare emission control. In particular, some means of calculating combustion efficiency and partial oxidation products is required.

The objective of this research is to extend previously developed technology to the analysis of flare systems. The theoretical model developed would be applied to evaluating combustion modifications applicable to flaring (Section 7.1.4) and to the evaluation of the applicability of flaring to the control of gaseous emissions (Section 7.3).

8.1.2 Background

Analysis of turbulent combustion depends on combining turbulent mixing models with kinetic data for elementary reaction steps. Combustion rates are limited by turbulent mixing rates and are typically several orders of magnitude lower than theoretical even for highly efficient gas turbine combustors. No simple analytical methods have been developed.

When analyzing turbulent mixing problems it is customary to use empirical correlations to describe the transport rates because of the lack of useful theoretical formulations. Unfortunately, empirical correlations have not been developed which are suitable for detailed analysis of subsonic reacting flows because of the dearth of experimental data.

Numerical analysis techniques have recently become available for the precise analysis of temperature, composition and velocity profiles in reacting flows. Figure 8-1 illustrates the application of such a model to the analysis of a hydrogen diffusion flame, comparing theoretical predictions (Ref. 97) against experimental measurements (Ref. 98). The jet diameter was 7.62 mm. Jet velocity was 590 ft/sec.

The recommended research program would involve the application of present analytical capability to the measurement of combustion efficiencies, partial oxidation products, and nitrogen oxides formed in a diffusion flame analogous to an elevated flare system. The program would consist of the following parts:

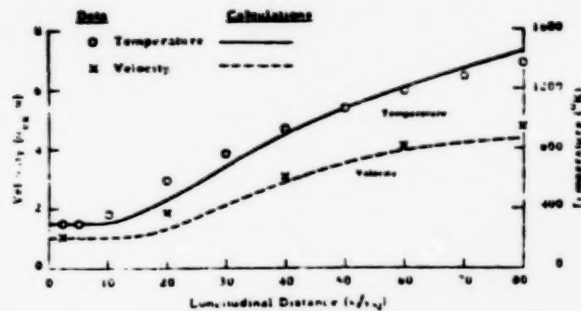
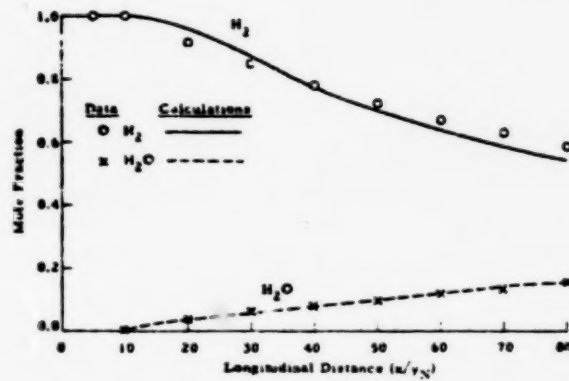


Fig. 8-1 - Comparison Between Measured and Calculated Centerline Distributions (Hydrogen Jet Exhausting into Air). Upper Figure: Species Distributions. Lower Figure: Temperature and Velocity Distributions (Ref. 97).

8.1.3 Validation of the Analytical Model

Sample cases would be run to check the validity of the selected analytical model for large diffusion flames. Data available in the literature would be summarized. Comparison would be made between predicted and experimentally measured flame properties for selected representative cases.

8.1.4 Evaluation of Flare Design Modifications

Representative cases would be run to evaluate the effect of combustion modifications applicable to flaring. Variables considered would include gas discharge velocity, burner diameter, flow distribution through multiple ports, effect of steam distribution and discharge velocity and substitution of air and oxygen for steam. Calculations would be made of emission rates of nitrogen oxides, partial oxidation products and soot or particulates. Combustion efficiencies would be calculated to estimate unburned hydrocarbons.

8.1.5 Priority

On a scale of A through E, the priority for research described in Sections 8.1.3 and 8.1.4 is A.

8.2 Evaluation of Remote Sampling Methods

8.2.1 Summary and Objectives

Elevated flare systems have eluded present sampling methods for reasons of remoteness and non-stoichiometric air-fuel dilution. Evaluation of remote sampling techniques for typical flare emissions is therefore needed.

8.2.2 Background

The problem of sampling elevated flare emissions is essentially one of accessibility. Flare stacks typically range from 200 to 400 feet in length with flames reaching 200 or 300 feet in emergency flaring. A summary of conventional sampling techniques and application to flare systems is presented in Section 6. Recently developed sampling methods which may be applicable rely on spectroscopic techniques and may include laser sources.

8.2.3 Summary of Remote Sampling Technology

Remote sampling methods and instrumentation would be summarized according to cost, performance and availability. For each instrument selected as applicable to flare emissions monitoring, instrument range, sensitivity and other operating characteristics such as drift and reproducibility would be included. Complete monitoring systems would be

chosen based on suitable components and auxiliaries. Instrument manufacturers would be contacted for complete instrument specification and other available performance data based on previous applications.

8.2.4 Remote Sampling Field Studies

A remote sampling unit would be selected or assembled for components for field testing at selected locations. Emissions measured would include particulates, hydrocarbon classes, nitrogen and sulfur oxides and hydrocarbon oxide classes. Resolution of emission classes would be defined.

8.2.5 Priority

On a scale of A through E, the priority for research described in Sections 8.2.3 and 8.2.4 is C.

8.3 Application of Flaring to Control of Gaseous Emissions

8.3.1 Summary and Objectives

The objective of the following research program would be to evaluate the potential of flaring as a means of pollution control. Guidelines for determining the suitability of given waste streams for flaring would also be established.

8.3.2 Background

The application of flaring for controlling gaseous emission promises to be a relatively inexpensive means of pollution control when compared to conventional methods such as incineration. Flaring has been applied to odor control in removal of trace quantities of $\text{NH}(\text{CH}_3)_2$. In this application, flaring was reportedly more effective than other methods of control (Ref. 3). Application of flaring to other streams and components requires experimental confirmation of effectiveness for reasons discussed previously, i.e., lack of suitable theoretical and experimental data for large turbulent diffusion flames.

A list of the types and magnitudes of emissions from petrochemical manufacturing is given in Table 8-1. Of these, emission control by flaring is most promising for those emissions which are themselves combustion intermediates: organic acids and anhydrides, esters, ethers and oxides. These constitute a large part of present petrochemical emissions.

8.3.3 Theoretical Analysis

Theoretical analysis of combustion products and efficiencies would be conducted for selected components and conventional flare systems. The modeling technique described in Section 8.1 or similar techniques would be used for the analysis. Maximum concentration limits and other operating conditions would be defined.

Table 8-1

EMISSIONS FROM PETROCHEMICAL MANUFACTURE, MM LBS (Ref. 15)

	1965	1970	1980	1990	2000
Non-aromatic Hydrocarbons					
acetylene	2.1	1.9	1.2	0.7	0.4
butadiene	14.4	14.0	21.9	59.7	78.0
cyclohexane	3.0	3.4	8.6	21.4	53.1
ethylene	33.5	41.6	100.9	376.5	1,004.2
higher olefins	6.3	7.9	7.3	7.9	7.9
propylene	14.0	17.3	41.5	108.7	270.4
Total	73.9	89.1	235.9	574.9	1,460.4
Aromatic Hydrocarbons					
benzene	16.3	19.1	42.6	95.6	224.1
styrene	6.5	6.5	19.9	51.4	126.1
toluene	6.0	6.4	2.3	14.0	19.9
xylene	3.2	2.6	4.2	6.8	11.2
Total	32.0	34.6	75.2	167.8	379.6
Organic Halides					
allyl chloride	0.6	0.7	0.9	1.3	1.9
benzylchloride	0.1	0.1	0.1	0.2	0.3
dichlorobenzenes	0.2	0.2	0.3	0.5	0.7
ethyl chloride	13.7	13.8	67.6	193.7	500.2
methyl halides	0.7	0.9	1.8	4.3	10.2
vinyl chloride	1.3	1.2	0.7	0.5	0.3
Total	16.6	16.9	71.4	200.5	573.9
Organic Acids and Anhydrides					
acetic acid	0.1	0.2	0.2	0.8	1.8
maleic anhydride	0.5	0.5	1.3	3.3	6.7
phenol	3.1	4.8	2.4	22.7	50.7
xylene base acids	3.2	2.6	4.2	6.8	11.2
Total	6.9	7.1	15.2	33.6	78.4
Alcohols					
butyl alcohols	0.8	1.0	1.8	3.4	4.5
ethyl alcohol	2.6	2.8	3.8	5.3	7.3
isooctyl alcohol	0.5	0.7	1.4	2.6	3.4
isopropyl alcohol	3.8	4.0	6.0	8.9	13.6
methyl alcohol	8.0	10.4	21.1	50.6	118.0
Total	15.8	18.9	34.1	70.8	146.8

Table 8-1 (Concluded)

	1966	1970	1975	1990	2000
Aldehydes					
acetaldehyde	1.2	1.4	3.3	7.7	18.1
acrolein	0.1	0.1	0.3	0.7	1.5
butyraldehyde	1.5	1.6	3.5	7.7	16.9
formaldehyde	2.6	3.3	6.7	16.1	37.5
Total	5.4	6.4	13.8	32.2	74.0
Nitrogen-organics					
acrylonitrile	3.7	4.6	9.7	21.8	67.1
aniline	0.5	0.5	0.9	1.6	2.5
methyl amines	0.3	0.3	0.7	1.6	3.7
toluene diisocyanate	0.5	0.5	0.8	1.1	1.6
Total	5.0	5.9	12.1	26.1	74.9
Esters, Ethers, Oxides					
acrylates	1.5	1.6	2.4	5.3	12.0
ethylene oxide	7.1	8.8	20.0	45.4	101.5
glycol ethers	0.3	0.4	0.9	2.1	4.8
propylene oxide	2.1	2.8	10.6	28.2	70.8
Total	10.8	13.6	33.9	81.0	199.1
Ketones					
acetone	1.2	1.5	4.5	12.7	35.2
Total Petrochemical	167.6	194.0	484.0	1,199.6	3,020.9

8.3.4 Experimental Analysis

This study would define experimental techniques and sampling methods for evaluating industrial flaring as applied to pollution control. The main result of the study would be a user guide with recommendations for determining the suitability of a given waste stream for flaring.

A pilot-scale flare burner and combustion chamber would be constructed. Suitable sampling techniques would also be developed. Components selected from Table 8-1 and at least one component evaluated as part of the study outlined in Section 8.3.3 would be tested using the pilot flare burner.

For each component selected for testing, operating conditions would be varied to determine optimum conditions for pollution control. Effects of flame stability and turbulence level on the production of pollutants would be determined.

8.3.5 Priority

On a scale of A through E, the priority of research described in Section 8.3.3 is A. The priority of research described in Section 8.3.4 is B.

An experimental study almost identical to that described in Section 8.3.4 has been recommended as part of the Federal R&D Plan for Air Pollution Control by Combustion-Process Modification (Ref. 99):

The objective is to determine the effect of turbulence and fuel type on the production of pollutants in turbulent diffusion flames with gaseous fuels. A large burner is recommended for this study, especially if the level of effort is minimum. Turbulence scale and intensity should be the major variables considered. The effect of fuel type should also be investigated. Special instrumentation might have to be developed for solving problems related to the effect of "unmixedness" on the production of pollutants. Attention would be given to the part that flame stability plays in the production of pollutants. The rationale and incentive for this proposed research (R&D Opportunity: VIII-22) is that many industrial flames are of the turbulent-diffusion-flame type. The research would provide guidelines for the optimization of turbulent conditions in gaseous-fuel combustion systems to minimize pollutant emission and form a basis for studies of other fuels burned in like manner. The relative overall priority rated for this research is 2 on a scale of 1 through 5.

8.4 Economic Analysis of Waste Stream Recovery and Alternate Disposal Methods

8.4.1 Summary and Objectives

An inventory of waste streams currently being flared is being compiled by means of a questionnaire as part of this Task Order. Waste streams burned in flares represent a potential loss of profit as well as a source of

gaseous and particulate emissions. For these reasons, and in order to define a basis for pollution control purposes, the economic basis for flaring as opposed to stream recovery or alternate disposal methods is needed.

8.4.2 Background

There are numerous gaseous plant emissions which are disposed of by means of flaring which are not associated with outright emergencies. These include:

1. Low pressure vent gases (Ref. 100) from an absorber. These gases contain light hydrocarbons, methane, ethane and propane plus oil droplets. The heating value of these discharged gases will not vary appreciably.
2. Partial Condenser Vent Gases. These gases may contain water and oil droplets (Ref. 100).
3. Disposal of off-spec or excess product (Ref. 23). This disposal problem is most frequent during plant start up which may last for periods up to about one year.
4. Leakage of gas through safety valves and block valves. Valve leakage to flare during routine operation of a 550 million-pound-per-year ethylene unit has been estimated at 4,000 lb/hr (Ref. 23).
5. Disposal of by-product streams which are produced in quantities too small or of insufficient purity for economical recovery (Ref. 23).
6. Venting of fuel and product storage tanks and loading platforms.

Gases which are sent to the flare system from the above sources are produced in quantities which can be estimated and for which storage for sale, recycling to process units or use as fuel in heaters and incinerators appear to be practical alternatives. For this reason guidelines need to be established to aid in determining these situations in which alternatives to flaring are reasonable. The following research program is recommended:

8.4.3 Identify Economic Considerations Now Used to Determine Whether a Given Flared Stream has Sufficient By-Product Value for Recovery

Representative processes would be chosen for evaluation from the process industries. By-product and waste streams would be listed for chosen processes. Stream composition and volume and recovery conditions (temperature and pressure) would be listed for each process stream along with recovery value, capital, operating and utilities costs for recovery and end use.

8.4.4 Identify Alternative Uses of Low Pressure Flammable Hydrocarbon Gases

Waste streams sent to the flare system are usually available at relatively low pressure. Suggested or potential uses for such streams would be identified and evaluated. One such suggested use which seems reasonable is the use of the waste stream for afterburner fuel gas (Ref. 100).

8.4.5 Evaluation of Alternative Disposal Methods

For the processes and waste streams selected for economic analysis in Section 7.4.3, alternative disposal methods such as incineration, adsorption, absorption, scrubbing and filtration would be identified. These would be evaluated for technical and economic feasibility.

8.4.6 Priority

On a scale of A through E, the priority of research described in Sections 8.4.3, 8.4.4 and 8.4.5 is D.

8.5 Emission Factors for Elevated Flare Systems

8.5.1 Summary and Objectives

The objective of the study would be to recommend the best available method for sampling and analysis of gaseous flare emissions and conduct field testing of elevated flare systems.

8.5.2 Background

Very little information on elevated flare emissions is available as has been discussed previously in several sections of this report. Furthermore, the validity of the fragmentary information available is unknown.

Based on our conversations with flare vendors and a major chemical manufacturing firm, two methods of sampling elevated flare emissions were identified, direct probe sampling and tracer-assisted probe sampling. Direct probe sampling involves inserting a probe into the exhaust plume beyond the flame boundary and is therefore strongly dependent on probe location. The use of a tracer aids the sampling technique by allowing a correction for dilution of the plume by ambient air.

These techniques are preliminary and many other improvements are foreseen. For example, the use of heavy and light tracers in conjunction may allow a further correction for buoyant and diffusion forces and a measurement of reliability; if the measured dilution of both tracers is the same, the air dilution factor can be calculated without consideration of the buoyancy factor.

In addition to air dilution problems, the direct sampling methods are complicated by accessibility to the plume, and other problems which typically arise in direct source sampling such as the requirement for rapid quenching of reaction products, condensation of liquid products in the probe and correction for the finite sampling and analysis times involved (Ref. 39). Of these, plume accessibility appears to be the most difficult obstacle; methods used have involved either a construction derrick or a long pole to support the sampling probe. Other methods considered have involved the use of helicopter borne sampling equipment. In general, these methods tend to be dangerous, cumbersome and expensive. Improvements envisioned in this area include the use of fixed supporting structures taller than the flare stack and at a safe distance from which boom lowering of the probe into the plume would be practical. For steady-state emissions over long periods of time, the problem of flare sampling is not significantly different from stack gas sampling using multiple receptor locations relatively close to ground level. Such receptor methods normally require a relatively isolated source and require a relatively large number of points for a statistically reliable estimate of the source strength. Such requirements are rarely met with flares.

8.5.3 Site Selection and Evaluation of Sampling Methods and Hardware

From a survey of sampling and analytical techniques now in use, a sampling system would be chosen which is best suited to the problem of monitoring source emissions from flares, and a program developed for the determination of emissions factors. Emissions considered would include hydrocarbons, NO_x , SO_x , particulates and partial oxidation products such as CO and aldehydes. The sampling and analysis technique would be suitable for emissions monitoring of sudden upsets as well as steady-state flow. The duration of plant upsets may be from a few minutes up to a maximum of about one hour (Ref. 10). During major upsets, discharge of several hundred thousand pounds per hour to the flare is common with resulting flame lengths of several hundred feet and combustion rates upwards of a billion Btu's per hour (Ref. 30). Testing sites would be selected from among industrial locations and experimental flare systems furnished by manufacturers of combustion equipment. At least one site would be chosen from the hydrocarbon process industries.

8.5.4 Field Testing of Elevated Flare Systems

Field testing would involve the measurement of emission factors at selected sites. Analysis of data would include an estimation of precision. Analysis of the emissions from the selected plant site(s) would include an inventory of flared streams and measured emissions on a day-to-day basis for a period of time long enough to give an indication of typical plant flaring practices.

8.5.5 Priority

On a scale of A through E, the priority for the research outlined in Sections 8.5.3 and 8.5.4 would be A.

SECTION IX

REFERENCES

1. Reed, R. D., Furnace Operations, Gulf Publishing Co., Houston, Texas, 1973.
2. Scheers, A. H., "Veiligheidssystemen en luchtverontreiniging," Pt. Procestechneik, Vol. 28, No. (6)-(13), 1973.
3. Byrd, J. F., "Solving a Major Odor Problem in a Chemical Process," Paper No. 63-35, APCA Conference, June 1963.
4. American Petroleum Institute, API Manual on Disposal of Refinery Wastes, Vol. II, "Waste Gases and Particulate Matter," 5th edition, New York, 1957.
5. Danielson, J. A., ed., "Air Pollution Engineering Manual," Air Pollution Control Dist., County of Los Angeles, U. S. Dept. of Health, Education and Welfare, Public Health Service, Cincinnati, Ohio, 1967.
6. Horton, B. B., Master, N., and Wedel, R. T., "Approaches to the Design of Flare Systems," Presented at Session 8, "Offsite Facilities," ASME Petroleum Mechanical Engineering Conf., Los Angeles, 17 September 1973.
7. Stewert, R. M., "High Integrity Protective Systems," Instn. Chem. Engrs. Symposium Series No. 34, London, 1971.
8. Lawler, J. B., "Cut Costs on Flare Stack Design," Hydrocarbon Process., Vol. 46, No. 9, September 1967, pp. 139-142.
9. Vanderlinde, L. G., "State of the Art Review of Smokeless Flares," Paper presented at the Regional Meeting, Gulf Coast Gas Processors Association, Corpus Christi, Texas, 21 February 1974.
10. Communication Between M. G. Klett and John F. Straitz, III, National AirOil Burner Company, Inc., 26 March 1974.
11. Communication Between M. G. Klett and Mick Sanderson, Flaregas Corporation, 22 March 1974.
12. American Petroleum Institute, "Guide for Pressure Relief and Depressuring Systems," API RP 521, Washington, D. C., 1969.
13. Tan, S. H., "Flare System Design Simplified," Hydrocarbon Process, Vol. 46, No. 1, January 1967, pp. 209-212.
14. Kent, G. R., "Practical Design of Flare Stacks," Hydrocarbon Process., Vol. 43, No. 8, August 1964, pp. 121-125.

15. Rolke, R. W. et al., "Afterburner Systems Study," EPA-R2-72-062, Environmental Protection Agency, Washington, D. C., August 1972.
16. Gaydon, A. G., and Wolfhard, H. G., Flames, Their Structure, Radiation and Temperature, Third Edition Revised, Chapman and Hall, London, 1970.
17. Horton, B. B. et al., "Approaches to the Design of Flare Systems," Paper presented at Session 8, Offsite Facilities," ASME Petro. Mech. Engr. Conf., Los Angeles, 17 September 1973.
18. Seebold, J. G., "Curing Flare Systems Noise Provides Major Challenge," Can. Petrol., January 1973, p. 53.
19. Seebold, J. G., and Hersh, A. S., "Refinery Flare System Injectors Redesigned for Noise Control," Paper presented at the Petro. Div., ASME, New York, 1970.
20. Shore, D., "Toward Quieter Flaring," CEP, Vol. 69, No. 10, October 1973, pp. 60-64.
21. Bragg, S. L., "Combustion Noise," J. Inst. Fuel, January 1963.
22. London, D. E., "Requirements for Safe Discharge of Hydrocarbons to Atmosphere," Proc. API Division of Refining, Vol. 43 (III), 1963, pp. 418-433.
23. Kent, G. R., "Make Profit from Flares," Hydrocarbon Process., October 1972, pp. 121-123.
24. Werchan, R. E., and Bruce, R. D., "Process Plan Noise Can be Controlled," CEP Vol. 69, No. 10, October 1973, pp. 51-55.
25. Palmer, H. B., Cullis, C. F., "The Formation of Carbon from Gases," Chemistry and Physics of Carbon, Vol. I, P. L. Walker, Ed., Marcel Dekker, Inc., New York, 1965.
26. Parker, W. G., and Woldhard, H. G., J. Chem. Soc., p. 2038, 1950.
27. Communication Between M. G. Keltt and Robert Schwartz, John Zink Company, 8 February 1974.
28. Lauderback, W., "Unique Flow System Retards Smoke," Hydrocarbon Process., June 1972, pp. 127-128.
29. Powell, D. T., and Schwartz, R. E., "Borco Uses Low-Level Flare at Freeport," Oil and Gas Journal, 19 June 1972, pp. 62-63.

30. Brzustowski, T. A., and E. C. Sommer, Jr., "Predicting Radiant Heating from Flares," Preprint No. 64-73, API Division of Refining, Philadelphia, Pa., 1973.
31. Sussman, V. H., Palmer, R. K., Bonanana, F., Steigerwald, B. J., and Lunche, R. G., "Emissions to the Atmosphere from Eight Miscellaneous Sources in Oil Refineries," Report No. 8, Joint District Federal, and State Project for Evaluation of Refinery Emissions, Los Angeles County Air Pollution Control District, Los Angeles, June 1958.
32. Haagen-Smit, A. J., "Chemistry and Physiology of Los Angeles Smog," T&EC, Vol. 44, No. 6, June 1952, pp. 1342-1346.
33. Cantwell, J. E., and Bryant, R. E., "How to Avoid Piping Failures in: (1) Corrosion by Liquid Metal Attack, (2) Flare Tips by Severe Cracking," Hydrocarbon Process., May 1973, pp. 114-117.
34. Sternling, C. V., and Wendt, J. D. L., "On the Oxidation of Fuel Nitrogen in a Diffusion Flame," AIChE J., Vol. 20, No. 1, January 1974, pp. 81-87.
35. Reed, R. D., "Design and Operation of Flare Systems," CEP, Vol. 64, No. 6, June 1968, pp. 53-57.
36. Bodurtha, F. T., Palmer, P. A. and Walsh, W. H., "Discharge of Heavy Gases from Relief Valves," CEP, Vol. 69, No. 4, April 1973, pp. 37-41.
37. Pasquill, F., "The Estimation of the Dispersion of Windborne Material," Meteorol. Mag., Vol. 90, No. 1063, February 1961, pp. 33-49.
38. Bosanquet, C. H., and Pearson, J. L., "The Spread of Smoke and Gases from Chimneys," Trans. Faraday Soc., Vol. 32, 1936, pp. 1249-1264.
39. Turner, D. B., Workbook of Atmospheric Dispersion Estimates, U. S. Dept. Health, Education and Welfare, Pub. Health Service Rept. No. 999-AP-26, Cincinnati, Ohio, Rev. 1969.
40. Carpenter, S. B. et al., "Principal Plume Dispersion Models: TVA Power Plants," APCA J., Vol. 21, No. 8, August 1971, pp. 491-495.
41. Coward, H. F., and Jones, G. W., "Limits of Flammability of Gases and Vapors," U. S. Bureau of Mines, Bulletin No. 503, 1952.
42. Jones, G. W., "Fire and Explosion Hazards of Combustible Gases and Vapors," in Industrial Hygiene and Toxicology, Vol. 1, 2nd ed., Interscience, New York, 1958.

43. Factory Mutual Engineering Corp., Handbook of Industrial Loss Prevention, 2nd ed., McGraw Hill, New York, 1967.
44. Zabetakis, M. G., "Flammability Characteristics of Combustible Gases and Vapors," U. S. Bureau of Mines Bulletin 627, 1965.
45. Sutton, O. G., "A Theory of Eddy Diffusion in the Atmosphere," Proc. Roy. Soc., London, A, 135, 1932, pp. 143-165.
46. Constance, J. D., "Calculate Effective Stack Height Quickly," Chem. Eng., 4 September 1972, pp. 81-83.
47. Holland, J. Z., "A Meteorological Survey of the Oak Ridge Area," AEC Rept. No. ORD-99, Washington, D. C., 1953, p. 584.
48. Briggs, G. A., "Plume Rise," AEC Critical Review Series, TID-25075, 1969.
49. Heitner, I., "A Critical Look at API RP 521," Hydrocarbon Process., November 1970, pp. 209-212.
50. Clean Air Amendments of 1970, PL 91-604.
51. "National Primary and Secondary Ambient Air Quality Standards," Federal Register, 36, No. 84, 8186-8201, 30 April 1971.
52. "Proposed Sulfur Oxides Secondary Standards," Federal Register, Vol. 38, No. 87, 7 May 1973, pp. 11355-11356.
53. "Standard of Performance for New Stationary Sources," Federal Register, Vol. 39, No. 47, 8 March 1974.
54. "Title 40 - Protection of Environment," Federal Register, Vol. 36, No. 228, 25 November 1971, pp. 22369-22480.
55. "National Emission Standards for Hazardous Air Pollutants," Federal Register, Vol. 30, No. 234, 7 December 1971, pp. 23239-23256.
56. King, W. R., "Air Pollution Control," Riegel's Handbook of Industrial Chemistry, James Kent, ed., Van Nostrand Reinhold Co., New York, 1974.
57. Dubko, S. L., "Air Pollution Control at Gas Processing and Sulfur Recovery Plants," Department of Health, Government of Alberta, Canada, February 1969.
58. "Compilation of Air Pollutant Emission Factors," U. S. Environmental Protection Agency, Office of Air Programs, OAP Publication No. AP-42, Research Triangle Park, N. C., March 1973.
59. "Guide for Compiling a Comprehensive Emission Inventory," U. S. Environmental Protection Agency, Publication No. APTD-1135, Research Triangle Park, N. C., March 1973.

60. Cross, F. L., "Environmental Aspects of Site Selection for a Petroleum Refinery," Proceedings of the Fourth Annual Northeastern Regional Antipollution Conference, University of Rhode Island, 15 July 1971.
61. International Petroleum Encyclopedia 1973, Petroleum Publishing Co., Tulsa, Okla., 1973.
62. Husa, H. W., "How to Compute Safe Purge Rates," Hydrocarbon Process, Petrol. Refiner, Vol. 43, No. 5, May 1964, pp. 179-182.
63. Bluhm, W. C., "Safe Operation of Refinery Flare Systems," Paper presented at 26th Meeting, API Division of Refining, Houston, Texas, 10 May 1961.
64. Reed, R. D., US 3, 055, 417, Assigned to John Zink Company.
65. John Zink Company Sales Folder MS12732MA.
66. National AirOil Burner Co., Inc., Bulletin No. 38, 1972.
67. Gibson, R. O., and D. J. Vinson, "Smokeless Flares Installed at Gasoline Plants," Oil and Gas Journal, 4 December 1972, pp. 75-77.
68. Peterson, P., "Explosions in Flare Stacks," Presented at AIChE Petrochemical Exposition, Houston, Texas, 21 February 1967.
69. Patterson, G. C., "Fundamentals of Engineering Offsites and Utilities for the HPI, Part 6, Pressure Relief and Blowdown," Petrol. Chem. Engr., May 1967, pp. 53-58.
70. Lapple, C. E., and Shepherd, C. B., "Calculation of Particle Trajectories," Ind. Eng. Chem., Vol. 32, 1940, pp. 605-617.
71. Craven, A. D., "Thermal Radiation Hazards from the Ignition of Emergency Vents," Paper presented at Symp. on Process Hazards, Inst. of Chem. Engineers, N. W. Branch, Manchester, England, April 1972.
72. Zabetakis, M. G., and Burgen, D. S., "Research on the Hazards Associated with the Production and Handling of Liquid Nitrogen," Bureau of Mines Report, Invest. 5707, U. S. Dept. Interior, Washington, D. C., 1961.
73. Kent, G. R., "Find Radiation Effect of Flares," Hydrocarbon Process., Vol. 47, No. 6, June 1968, pp. 119-130.
74. Hawthorne, W. R., Weddell, D. S., and Hottel, H. C., Third Symposium on Combustion and Flame and Explosion Phenomena, Williams & Wilkins, Baltimore, 1949.

75. Lewis, B., and von Elbe, G., Combustion, Flames and Explosions of Gases, Second Edition, Academic Press, New York, 1961
76. Kent, G. R., "Practical Design of Flare Stacks," Hydrocarbon Process. and Petrol. Refiner, Vol. 43, No. 8, August 1964, pp. 121-125.
77. Hoehne, V. D., and Luce, R. G., "The Effect of Velocity, Temperature, and Molecular Weight on Flammability Limits in Wind-Blown Jets of Hydrocarbon Gases," API Preprint No. 56-70, 1970.
78. Brzustowski, T. A., "A Model for Predicting the Shapes and Lengths of Turbulent Flames Over Elevated Industrial Flares," Presented at the 22nd Can. Chem. Eng. Conf., Toronto, 1972.
79. Ban, S. D., Summary Report on Zelten Flare Radiation Study, Battelle Memorial Inst., Columbus, Ohio, 1970 (draft).
80. Grumer, J. et al., "Hydrogen Flare Stack Diffusion Flames: Low and High Flow Instabilities, Burning Rates, Dilution Limits, Temperatures, and Wind Effects," Bureau of Mines Rept., Invest. 7457, U.S. Dept. Interior, Washington, D.C., 1970.
81. Chomiak, J., "A Possible Propagation Mechanism of Turbulent Flames at High Reynolds Numbers," Combustion and Flame, Vol. 15.
82. Hottel, H. C., "Radiant Heat Transmission," in W. H. McAdams, Heat Transmission, 3rd Edition, McGraw-Hill, New York, 1954, pp. 51-125.
83. Chemical Engineers' Handbook, ed. R. H. Perry, C. H. Chilton and S. D. Kirkpatrick, 4th ed., 5-133, McGraw-Hill, New York, 1963.
84. "Flow of Fluids Through Valves, Fittings, and Pipe," Tech. Paper 410, Crane Co., 1957.
85. Leithe, W., The Analysis of Air Pollutants, Ann Arbor-Humphrey Science Publishers, Ann Arbor, Mich., 1970.
86. Morrow, N. L., Brief, R. S., and Bertrand, R. R., "Air Pollution Analysis," Chemical Engineering, 24 January 1972.
87. Lengelle, G., and Verdier, L., Gas Sampling and Analysis in Combustion Phenomena, NATO Advisory Group for Aerospace Research and Development, AGARDograph No. 168, July 1973.
88. Coloff, S. G., "Ambient Air Monitoring of Gaseous Pollutants," American Laboratory, July 1973.

89. West, P. W., and Gaeke, A. G., Anal. Chem. Vol. 28, p. 1816, 1956.
90. Kildal, H., and Byer, R. L., "Comparison of Laser Methods for the Remote Detection of Atmospheric Pollutants," Proc. IEEE, Vol. 59, No. 12, p. 1645.
91. Measures, R. M., "A Comparative Study of Laser Methods of Air Pollution Mapping," Institute of Aerospace Studies, University of Toronto, Canada, UTIAS Report No. 174.
92. Hodgeson, J. A., McClenny, W. A., and Haust, P. L., "Air Pollution Monitoring by Advanced Spectroscopic Techniques," Science, Vol. 82, 19 October 1973.
93. Davis, S. I., Applied Optics, Vol. 5, p. 139, 1966.
94. Snowman, L. R., and Gillmeister, R. J., Paper 71-1059, presented at the Joint Conference on Sensing of Environmental Pollutants, Palo Alto, Calif., November 1971.
95. American Gas Association Monthly, 57, No. 2, February 1975.
96. Chase, R. L., and George, R. E., "Contaminant Emissions from the Combustion of Fuels," JAPA, Vol. 10, No. 1, February 1960.
97. Mikatarian, R. R., and Benefield, J. W., "Turbulence in Chemical Lasers," Paper No. 74-148, AIAA 12th Aerospace Sciences Meeting, Washington, D. C., February 1974.
98. Kent, J. H., and Bilger, R. W., "Turbulent Diffusion Flames," TN F-37, The University of Sydney, Australia, 1972.
99. Battelle Memorial Institute, "The Federal R&D Plan for Air Pollution Control by Combustion-Process Modification," Final Report, EPA Contract CPA 22-69-147, Columbus, Ohio, 11 January 1971.
100. Weekley, G. H., Jr., and Sheelon, F. R., "Jet Compressors Recover Waste Gases," Hydrocarbon Process., Vol. 49, No. 10, October 1966, pp. 165-170.